THE ROLE OF KINESTHESIS IN THE ORGANIZATION OF SPEECH ORGAN MOVEMENT

CYNTHIA GROVER

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BY

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of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

This thesis investigates position sense in the tongue and the role of kinesthesis in organizing voluntary rhythmic human finger movements and the repetition of monosyllables.

Four experiments showed that a sense of the tongue's position inside and outside the mouth in horizontal and vertical planes exists, and is similarly accurate to that of the limbs (error: 2°). Subjects misjudged the position of their tongue following loading of the tongue. Anesthesia of the mucosa did not reliably reduce the accuracy of lingual position sense. The sources of positional information that contribute to position sense in the tongue and limb are similar: muscle, tendon, skin and knowledge of efference.

Six experiments revealed that finger movements and monosyllable repetition entrained to an imposed, irrelevant kinesthetic rhythm in about 30% of the data, although subjects were not instructed to entrain their finger movements or speech to the kinesthetic stimulus rhythms. As entrainment should not have arisen at all unless the organization of both finger movement and monosyllabic speech has the character of a system of non-linear oscillators, this is a powerful finding.

The entrainment commonly features a slight anticipation of antiphase of the kinesthetic stimulus using both finger movement and speech tasks. Subjects entrained their speech and finger movements to the stimulus rhythms equally often, upholding the thesis that, at a fundamental level, speech and finger movements are organized similarly. Kinesthetic information is used to organize voluntary limb and speech movements.

Keywords: tongue, speech movement, finger movement, kinesthesis, position sense, proprioception, post-contraction, effort, rhythm, non-linear oscillator

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LIST OF ABBREVIATIONS

The following abbreviations and terms are used in this thesis.

ms	milliseconds
F_0	fundamental frequency
[..]	The International Phonetic Alphabet is used frequently to represent English sounds, since the English spelling system commonly does not represent one sound uniquely with one symbol. Common sounds referred to in this thesis and English words that illustrate the sounds are:

Initial consonants

Sound	Word	Sound	Word	Sound	Word
[b]	boot	[d]	door	[g]	game
[s]	suit	[s]	shoe		

Vowels

Sound	Word	Sound	Word	Sound	Word
[æ]	bat	[ɛ]	fen	[ɪ]	bin
[ɔ]	gone	[ʌ]	bun	[u]	goon
[o]	boat	[i]	seen	[ə]	sofa

CHAPTER 1

ORGANIZING MOVEMENT: INTRODUCTION

This thesis is concerned with the question of whether speech is organized in the same way as are other voluntary body movements. Central to this question is the extent to which sensation plays a role in the production of movement. We manipulate our environment by means of movement, while in complementary fashion, sensation informs us about the environment and about the position of body parts that can be deliberately moved to fulfil our purpose. It is reasonable to expect that a source that can reveal the current position of the body parts that are to be moved should be consulted prior to organizing the next movement.

For this type of positional information about limb movement we look to kinesthesis. It is clear from experiments on human subjects who point their finger to targets after adapting to vision through optical prisms that the sensed position of a limb informs the plan for subsequent arm movement (see Welch, 1978). However, researchers on speech have rarely incorporated kinesthesis into their models of speech production, although they commonly acknowledge that it must help in the process of organizing speech movement (eg. MacNeilage, 1970; Borden, 1979; Gracco & Abbs, 1986). The first question that this thesis asks is whether the position of the tongue, an important speech articulator, can be perceived, and so could be used to organize speech and other tongue movements.

It is sensible to suppose that information about limb position is important in organizing voluntary movements. In addition, when carrying out a series of repeated rhythmic movements, like drumming, the timing of one movement relative to the next should also be important (see Lashley, 1951). The focus of much modern research has been repeated rhythmic movement (eg. Bernstein, 1967; Gelfand, Gurfinkel, Tsetlin & Shik, 1971; Scholz & Kelso, 1989). In the last twenty-five years, numerous papers have demonstrated that rhythmic limb movement can be generated in lower vertebrates without reference to sensory information (eg. Shik & Orlovsky, 1967; Grillner, Buchanan, Wallen & Brodin, 1988; Lund & Enomoto, 1988). This has called into question the role of sensory information, whether positional or temporal, in organizing rhythmic movement.

Evidence showing that simultaneously moving limbs tend to move at harmonically related rhythms has increased (eg. von Holst & Mittelstaedt, 1950:1973; Bernstein, 1967; Scholz & Kelso, 1989 and 1990). These authors present their results as evidence of concurrent motor rhythms influencing one another, or as evidence of a single basic motor rhythm being used for all concurrent voluntary movement. It is possible that the influence is not motor-motor, but in fact sensory-motor, but this has been overlooked. If kinesthesis may guide one aspect of movement, namely limb positioning, why should it not be used to guide other aspects of the movement, such as the timing of the interaction of several limb movements ? It is sensible to suppose that the brain will use any relevant and available sensory information to produce movement that is tailored to the animal's capabilities and the environment's demands. Even if motor rhythm influences other motor rhythms, I argue that the rhythm of concurrent sensation may well influence the rhythm of repeated periodic movements.

English speech is perceived by native speakers to be rhythmic (Lehiste, 1977). It is legitimate to ask whether kinesthetic information might influence the rhythm of speech as well as that of body movement. This is the other question addressed by this thesis.

Speech provides an interesting testing ground for any theory of movement organization for several reasons. First, speech has numerous subcomponents which are executed in faster sequences than most other series of voluntary movements. The average speaker comfortably produces 20 or more different speech sounds (phonemes) per second. Articulation of a monosyllable (1 to 7 phonemes) can involve upwards of 70 muscles and 8 to 10 moveable body parts, so the movements are complex as well as fast (Gracco & Abbs, 1986). If a theory of movement production is truly general, it should be valid for fast and complex movements, like those of speech, as well as for slow movements, like those of the limbs.

Second, we speak without the aid of vision. Limb movements are commonly visually monitored, but we monitor our own speech by ear. Experimentation with speech allows expansion of the theoretical catchment area to a less commonly explored pairing of sensory modalities: kinesthesis and audition.

Third, speech is used for communication. We might suppose that the organization of speech has been tailored to fulfil this hugely important function, which is quite unlike the function of movement for most body parts. If so, then a theory of movement should be truly general if it is supported by results from experiments on speech as well as those on other moveable body parts.

1.1 The Role of Kinesthesis in Organizing Speech Production

This thesis is divided into two main parts. The first part reviews the role of kinesthesis in the study of voluntary movement, and describes four experiments on kinesthesis in the tongue (Chapters **1** to 7). Chapter **1** places the questions that the thesis asks about kinesthesis against a theoretical background; it reviews the use of the non-linear oscillator metaphor and the role of kinesthesis in the study of voluntary movement. Those who are already familiar with these fields of study may find it preferable to proceed to Chapter 2, which reviews the evidence for the existence of kinesthesis in the tongue. Chapters 3 to 6 describe four experiments on sensing tongue position, and Chapter 7 discusses the availability of kinesthesis for use in organizing speech.

Note that linguistic models of speech production do not contribute to this discussion, for their concern is the translation of a mental representation of a series of speech sounds (phonemes) into commands that could elicit muscular contraction (eg. Fry, 1966; Boomer & Laver, 1968; MacNeilage, 1970; Borden, 1979; Dell, 1988), rather than the organization of speech articulator movements by incoming sensory afference.

The second part of the thesis presents the argument that rhythmic speech movement could be open to kinesthetic influence. The research on sensory influences upon organizing speech movements and other rhythmic body movement is reviewed in Chapter 8. Chapter 9 lays out the theoretical expectations for six experiments on the role of kinesthetic stimulation in organizing speech and finger movement rhythm. The experimental methods are described in Chapter 10. The results are presented and discussed in Chapter 11. Chapter 12 concludes the thesis with a more general discussion.

1.2 The Organization of Movement: Definitions

I shall now put forward a formulation of the types of information used by the human brain to organize voluntary movement. Before proceeding further, definitions of basic terms are required.

1.2.1 Kinesthesis

Kinesthesis has been defined as the sensation of position and movement of body parts based on input other than visual and auditory information (Howard & Templeton, 1966, p.72). There are a number of sensations associated with kinesthesis (see Woodworth, 1903):

a. the felt static position of the limb
b. the sensation of movement as opposed to stillness
c. the sensations of direction, speed and amplitude of movement
d. the awareness that a movement is voluntary, rather than externally imposed
e. the sensation of resistance to movement.

Human subjects may report several of these sensations following a given experimental treatment (eg. Goodwin, McCloskey & Matthews, 1972; Craske, 1977), and so they are not mutually exclusive, and experimental treatments in general cannot easily separate them (but for recent progress, see Horch, Clark &

Burgess, 1975; Clark, Horch, Bach & Larson, 1979; Clark, Burgess, Chapin & Lipscomb, 1985; Clark, Burgess & Chapin, 1986; Taylor & McCloskey, 1990; Ferrell & Craske, in press).

1.2.2 Position sense

By position sense I mean the sensed static position of an organ or limb, as given in section **1.2.1** above. When subjects are asked to indicate the static position of a limb, they might tap a source of information that directly informs them of static limb position. For a moving limb, they might deduce current limb position by integrating over time the sensed velocity of movement from a known starting point. Thus, there is more than one potential basis for sensing position: movement of the limb, as well as position might serve. However, these alternatives should not be equally likely; it would be sensible to interrogate the sense that most directly informs, that is, the sense of static position, rather than taking what appears to be a more circuitous option. Thus, the ability to sense position should be of primary importance.

1.2.3 Sensory

'Sensory' refers to processes and elements in the nervous system that can give rise to conscious sensation. The import of this term is psychological, rather than physiological (see Dewey, 1896).

Afference from the sense organs, such as the muscle spindles, can be interpreted by the brain to yield sensation. It is worth noting that conscious sensation does not necessarily precede the organization of movement by afference from muscle spindles. Afference that may ultimately give rise to conscious sensation can influence movement execution at lower levels of the nervous system, for example, in the alpha-gamma loop at the spinal cord before ascending to the brain (Matthews, 1972 and 1982).

1.2.4 Motor

'Motor' refers to an efferent pattern of discharge generated in the nervous sytem that can induce the movement of a limb or organ. Previously, motor commands for voluntary movements were thought to issue exclusively from the brain (eg. Henry, 1953; Gibbs, 1954; Dewhurst, 1967). It is now clear that movements like walking on a treadmill can be generated in lower vertebrates at the spinal cord (eg. Shik & Orlovsky, 1976). Accordingly, 'motor' is used here to characterize efference from the brain, the brain stem, and the spinal cord that results in limb or organ movement.

1.2.5 Feedback

Feedback here will mean afference that arises from the moving limb as a direct consequence of a voluntary movement or of its motor efference, and which can provide information about the movement or guide subsequent movement. Thus, if the hand grasps a cup, the afference that contributes to the sensations of contact to a surface and the sensation of a new hand position is kinesthetic feedback.

At the level of the spinal cord (and the brain stem - see Rossignol, Lund & Drew, 1988), there is feedback from the spindle receptors to the alpha motoneurons, which finely tunes the closing of the grasp. It is important to note that this feedback may or may not give rise to conscious sensation, and may travel to the brain or to some lower motor center to guide movement under this definition. It is likely that the motor system employs several feedback systems that differ in scope and function (see Abbs, Gracco & Cole, 1984).

1.2.6 The corollary discharge

There is good logical evidence for a copy of the motor commands from the brain being compared to sensory afference from the moving limbs (Matthews, 1977; McCloskey, 1981; Gandevia, 1982; Jones, 1986). The efference copy is included in the meaning of 'corollary discharge' here. I use the term corollary discharge to mean a central neural discharge that remains wholly within the central nervous system and arises with or from a centrally issued motor command and is in some unknown way commensurate with it. The corollary discharge is a hypothetical construct.

Arguments in favor of a corollary discharge with respect to sensing eye and limb position have been put clearly and succinctly by McCloskey (1978 and 1981) and Matthews (1982). It is essential to know when the visual world has moved and when it is just one's own eyes that have moved, while the visual world is stable. The retinal afference is identical in the two situations. The spindle afference from the ocular muscles has been argued not to contribute prominently to sensing eye position (eg. Brindley & Merton, 1960). In this circumstance, one would not know when the eye muscles had rotated the eye, and when they had not, rendering ambiguous the retinal afference that implies movement. A knowledge of the outgoing motor commands to move the eye would disambiguate the afference, and so the corollary discharge has been called for on logical grounds.

With respect to sensing limb position, it has been pointed out (Matthews, 1982) that the afference from the limbs that might tell us about position is also ambiguous. Major contributors to position sense, the muscle spindle receptors, fire more or less strongly, depending upon a number of factors other than muscle length. A knowledge of muscle length could theoretically tell us a limb's position, but we would need to disentangle that information from the other information that the spindle firing patterns can convey (see below, Figure **1.3** and accompanying discussion). The most economical way to do this would be by matching a knowledge of the outgoing motor commands against the incoming afference. Thus the corollary discharge is again required.

In the normal case, the afference from the moving limb matches the corollary discharge, producing the perception that the attempted movement was successful. If a mismatch occurs, for example, if a tendon in the limb of interest has been vibrated, producing afference that is not due to voluntary movement, radically different sensations of position and movement can arise. This suggests that the matching process can be more complex than the simple subtraction associated with the term Efferenzkopie (von Holst & Mittelstaedt, 1950:1973). It is likely that the brain uses other information it may have about the motor task and consults other sources of pertinent sensory information, like vision, to compose a sensation when a mismatch between motor command and afference occurs.

1.2.7 Purpose in organizing movement

Voluntary movement is movement that is intended by the actor to fulfil a purpose. The fulfilment of purpose would seem to be a sensible reason for a voluntary movement. Then purpose may be said to determine broadly the type of movement, and to decide which limbs will make the movement.

Purpose guides the drafting of the motor plan (Turvey, 1977; Saltzman, 1979), particularly with respect to directing attention to one or another aspect of the plan and its execution (Saltzman, 1979). So, for example, if one wishes to walk, this purpose should result in the legs being specified as the limbs to be used. Further, this purpose should call forth from memory or else trigger the generation anew of a motor plan that will result in the translation of the body to a place forward while maintaining upright posture.

This does not mean that the intention to move must be subject to conscious concentration in order to elicit voluntary movement in all cases. One's purpose is sometimes scarcely consciously acknowledged for well-learned movements, like those required for driving a car.

We can only speculate about the forms or neural relations that represent purpose in the nervous system, and the relation of will to consciousness; these matters belong still to the province of philosophy. Nonetheless, purpose should be a causative precursor to a motor plan for human voluntary movement.

1.2.8 The motor plan

The motor plan translates purpose into high level motor commands. It elicits the efference that can ultimately induce the appropriate muscular contractions to achieve the actor's purpose. While its function may be defined, its form is not known and is treated as being abstract (eg. Turvey, 1977; Saltzman, 1979; Schmidt, 1982).

To specify motor commands that will fulfil the actor's purpose, the motor plan must have access to sensory information, for example, information about limb position or about the distance to a visual target. Then motor commands can be drafted or tailored to accommodate this information.

The motor plan probably specifies in the motor commands that it composes or tailors only the broad characteristics of the intended movement, such as the limbs to be used (implied from work by Craske & Craske, 1986), and the type of movement, for example, walking forward at slow speed, and a command to start or stop (see Turvey, 1977; Schmidt, 1982). It is now clear that many of the fine details of movement are specified at lower levels of the nervous system in animals. For example, the cyclic alternation of stepping when a cat walks can be organized at the spinal cord (Shik & Orlovsky, 1976). It seems plausible that the human spinal cord should have a similar type of movement specifier.

Many researchers have inferred the parameters of motor control to be force (eg. Gelfand et al, 1971; Turvey, 1977; Hollerbach, 1981; Schmidt, 1982); others have suggested that speed and direction of movement might be specified in some way (eg. Saltzman, 1979; Schmidt, 1982). Nonetheless, we lack solid evidence about the parameters of the motor plan, and about the levels of command at which each parameter might be valid.

It is not known if the motor plan must be created anew each time that a voluntary movement is intended. It seems likely that a motor plan can be stored in memory, to be summoned when necessary, since with practice, complex movements, like typing, can be carried out faster and more accurately.

1.3 The Organization of Movement by Kinesthesis: Theory

I argue for two functions for kinesthesis in organizing movement. First, kinesthesis should provide prerequisite information for moving a limb or organ to a spatial goal, for example, scratching an itchy spot on one's back. Plainly, the position of the limb and the position of the target must be known before the next movement can be planned.

Studies of adaptation have convincingly shown that subjects who gaze through optical prisms mispoint with a constant error (providing that they receive no sensory feedback), indicating that they use kinesthetic information to enable the execution of pointing movements, and visual information to locate the target (implied by experiments by Craske & Crawshaw, 1974a and 1975b; Welch, 1978). If allowed to view their arm as it points, subjects will recalibrate the arm's kinesthetic system by adjusting sensed position so that the arm comes to point accurately at the visual target, resulting in an after-effect of mispointing once the prisms are removed. Clearly, sensory information, both visual and kinesthetic, can be used to plan voluntary movements.

Second, kinesthesis is used to monitor movement that is occurring. During and after a movement, for example, brushing our teeth, we can monitor the movement of the hand with the toothbrush, relative to the body, even if we do not register the instantaneous position of the hand at every moment.

Much has been made of the monitoring and planning functions of kinesthesis in the literature. Given the label kinesthetic or proprioceptive <u>feedback</u>, kinesthetic information about a voluntary movement that has just been executed was once considered to be prerequisite to the issuance of motor commands for the next movement (eg. Henry, 1953; Gibbs, 1954; Dewhurst, 1967). Obviously, if movements like walking on a treadmill can procede without any sensory input in decerebrate animals, as Shik & Orlovsky (1976) have shown, then kinesthetic information is not a sine qua non for organizing movement without an obvious purpose in a rudimentary environment.

I see the role of kinesthetic information as that of specifying values on some of the important parameters, such as initial position of the limb, for a movement that is about to be made in a complex environment, of representing to consciousness new values on these parameters during and after movement, and of contributing to the brain's mapping of the environment by interacting with sensory information from other modalities such as vision.

The availability of sensory information to consciousness should permit an animal to make practical conscious decisions about movements. This is valuable. We can often recover balance after stumbling against an object, but only at the cost of sudden, unpredictable, muscular stress. Feedback mechanisms at the spinal cord can accomplish this. However, we prefer to maintain balance without incident, if possible. This we do by seeing the obstacle before reaching it and deciding to step over it. Kinesthetic information at our disposal allows us to lift a leg appropriately.

In light of the above definitions, diagrams of voluntary movement organization may be drawn up to represent how the following concepts fit together (see Figure **1.1** to **1.3**). These diagrams feature:

a. purpose as a precursor to the movement plan.

b. a movement plan that may be drafted from scratch or called up from memory. It has access to sensory information and can compose high level motor commands.

c. motor commands to the effector limbs and organs.

d. a corollary discharge that is accessible to the motor plan for comparing to afference.

e. afference from the spindle receptors in muscles that returns to the alpha motoneurons at the spinal cord.

f. afference from the spindle, joint, tendon and cutaneous receptors that travels to the brain.

g. a sensory map of the body's surface and the location of movable parts relative to the trunk.

In Figure **1.1**, we start with a purpose, may then search memory for a suitable motor plan, or create one anew. It is assumed that at least parts of most motor plans for voluntary movements of the adult human are stored in memory.

The motor plan may consult memory for values on important

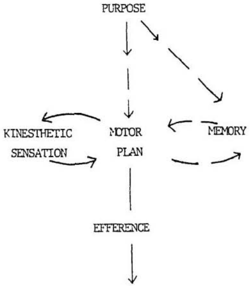

Figure 1.1 The first steps in organizing voluntary movement, once the purpose of the movement is known. Dashed line: optional path; solid line: compulsory path.

parameters, like speed or duration of movement (Woodworth, 1903) or force of muscular contraction (Schmidt, 1982), that have served successfully in the past to meet the demands of the task at hand. The motor plan should also consult the sensory register to find out current values on crucial parameters, like limb position.

After incorporating the information from memory and current sensation, the efference that will result in the elicitation of limb movement issues from the motor plan.

One should note that even if there is no explicit spatial target for the movement, knowledge of current limb position is necessary; if one is going to tap one's foot in time to music, one needs to know if the foot is already on the floor before starting to tap. If it is, then one lifts the foot; if not, one lowers it.

It is important to note that people who have lost sensation in a limb can move it to an intended position without prior kinesthetic information, depending instead upon vision (see Lashley, 1917; Sacks, 1972). It is then possible that there are default values for current limb position that memory supplies if current sensation is not available (Melzack & Bromage, 1973; Ferrell et al., in press). These default values might be the most recently registered values, or learned values (in the case of experimental animals). I am representing the case of the normal sentient human being in Figure **1.1**.

Figure **1.2** continues from Figure **1.1**. The efference issued by the motor plan now courses through the brain and out into the peripheral nervous system. In Figure 1.2, efference is issued according to the motor plan's instructions. A copy of the efference, in form of a corollary discharge, remains internal to the brain and

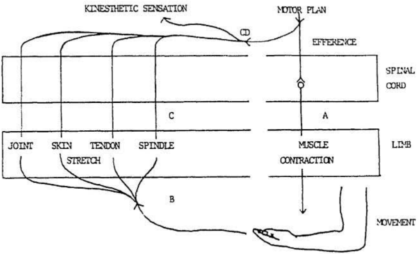

Figure 1.2. The interplay of movement organization and sensation. CD: corollary discharge. The breaks in the horizontal rectangles that represent the limb and spinal cord indicate a separation between afference and efference. A, B and C match A, B, and C, respectively on Figure 1.3, and are explained in reference to it.

limb position and movement.

Figure **1.3** supplies details not given in Figure **1.2**. The alpha motor meurons at the spinal cord not only elaborate motor commands based on the motor information from the brain, they may also modify the motor commands upon receiving afferent feedback from the limb.

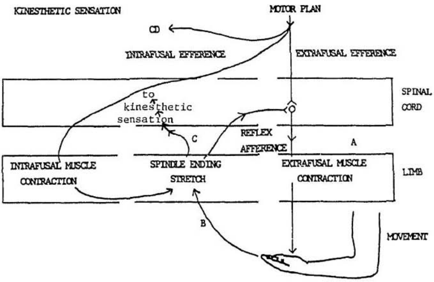

Figure 1.3. The alpha-gamma loop.

is matched against information that returns from the periphery (the four rising lines on the left of the diagram) after the intended movement has been carried out.

Various parts of the brain contribute to, or modify the efference in some way, as it passes to the spinal cord. For example, the cerebellum and motor cortex are known to be important in organizing and/or modifying movement commands (Carlson, 1977; Grillner, 1981). We do not know where or how the motor plan is represented in the brain, and so the motor centers have not been specified on this diagram.

The spinal cord transmits and issues motor commands that cause limb muscles to contract, producing limb movement. The movement stretches receptors in the skin, joint, tendon and intrafusal muscle of the limb. Sensory information from these receptors rises via the spinal cord to the brain, where it can be matched against the corollary discharge and interpreted, yielding information about limb position and/or movement that is available for conscious inspection. I refer to the registry of this kinesthetic information as a kinesthetic map.

It should be noted that the sensory information from the receptors may be interpreted without being matched against a corollary discharge. When movement is imposed by an external agent, there is no corollary discharge, yet we still are conscious of

The efference that is sent to the periphery consists of two kinds: efference that will trigger extrafusal muscle contraction and ultimately result in a limb movement (A in Figures **1.2** and **1.3**), and efference that causes the intrafusal muscle containing the spindles to contract. This second type of muscular drive is called gamma activation, and can be viewed as a way of priming the sensory receptors for the voluntary limb movement, and therefore muscle stretch, that will be caused by extrafusal muscle contraction (Matthews, 1977; Clark & Horch, 1986).

If the extrafusal muscle contraction is not appropriate for the level of spindle receptor firing set by gamma activation, then correction to the current motor commands may be made very quickly (within 30 ms (Cordo & Nashner, 1982)) via the reflex pathway from the spindle endings to the alpha motor neurons (Matthews, 1972; Clark & Horch, 1986). At that time, there need be no conscious awareness of the facts that the limb movement was not as expected and that a correction was made to rectify the problem. The rising arrow labelled C in Figures **1.2** and **1.3** indicates the afference that will eventually take a conscious form, following the presumed match against the corollary discharge.

Interpreting the afference from the spindle sensory endings is probably complicated; it should be noted that the spindles are not only primed by efference from the brain, but also are stretched mechanically by the moving limb (B in Figures **1.2** and **1.3**), for moving a limb changes muscle length in the limb. Stretching the extrafusal muscle causes the spindles in the intrafusal muscle to fire. The signal that arises from the spindle endings is complex, and is not thought to be likely to give rise when considered on its own to a straightforward measure of limb position or limb movement (see McCloskey, 1978 and 1981; Matthews, 1982). However, if a corollary discharge is assumed to be available following a voluntary limb movement, then afference from the spindle endings could be analysed to provide information about limb position and movement (Matthews, 1977; McCloskey, 1978 and 1981).

In any case, most voluntary movements involve pairs of simultaneously stretching antagonist and contracting agonist muscles. The brain receives afference from the spindles in both members of the pair, and the ambiguity of any one muscle's spindle discharge should be lessened in the presence of this fuller information. (Even silence from spindles in a contracting muscle can be useful information.)

The diagrams do not specify some important information. Namely, in a sequence of voluntary movements, particularly those which are repeated continuously, kinesthetic information need not be known prior to each successive movement. It is assumed that the cycle of movements might repeat under spinal cord control with relatively little contribution from the brain (see Delcomyn, 1980; Grillner, 1981), with afference returning to the spinal cord providing small and fast corrections to the movement in progress as necessary. These corrections, referred to in the older literature as reflexive, provide virtually instantaneous adjustment of movement (see Cordo & Nashner, 1982; Nashner & Forssberg, 1986).

While a limb's movement is monitored consciously, the ensuing kinesthetic afference may not arrive at the brain fast enough (time of travel: approximately 130 ms (Keele, 1982), but see Abbs, Gracco & Cole, (1984)) for it to correct a fast movement via conscious decision before it finishes.

I shall assume that this representation holds true for the organization of voluntary finger movement. It should hold true with minor adjustments for the organization of speech movements. There are several theoretical questions about movement in general that I turn to now, before proceeding to the application of these questions to finger and speech movements.

1.4 Problems in Movement Study

Any motor plan must meet certain criteria that have in the past been problematic for theories of movement organization.

Below, they are mentioned as the problems of degrees of freedom, of storage, of novelty, of accounting for the exhibition of patterned excitation at the spinal cord and the tendency to produce coordinated movement.

1.4.1 The degrees of freedom problem

The motor plan must be able to solicit simultaneous contractions of various qualities in many muscles at many joints. This is known in the literature (eg. Bernstein, 1967) as the degrees of freedom problem. It is inconceivable that the brain could individually and directly address each muscle of an active tennis player with timely commands for needed muscular contractions (contraction to a specific length at a certain speed and with a given force). The speed of nervous conduction is not sufficient for the wealth of information. This degrees of freedom problem also must apply to patterned sequences of movement, like chewing or walking, where movements of many muscles succeed each other rapidly.

It may be inferred that the brain directly specifies fewer movement details than an observation of the executed movement suggests are controlled. Accordingly, considerable authority is relegated by researchers to the spinal cord, and, in the case of speech, probably to the brain stem (see Lund & Enomoto, 1988;

Rossignol et al., 1988, with respect to chewing). This does not contradict the diagrams of sensory-motor organization (Figures **1.1**, **1.2** and **1.3**).

This delegation of much motor authority to lower centers helps also to ease the storage and the novelty problems that are delineated below.

1.4.2 The storage problem

It is not likely that all of the programs for our voluntary movements, replete with fine details, could be stored in memory.

I assume that broad characteristics of a movement to be executed can be stored as part of a motor plan and retrieved when needed. These characteristics would be items such as limbs involved, and limb position necessary to start the movement, and the force required. Current sensory information should also supply some of the necessary details for the upcoming movement (see below, section **1.4.3**).

It should be noted that some of the details of movement may not be programmed at any level, but are a consequence of specified parameters. For example, if, in squash, a great deal of power is specified for the next racquet stroke, and greater force than usual is issued, then the arm will probably be moving faster than usual when the racquet contacts the ball. The increase in speed need not be specified if there is a requested increase in power.

1.4.3 The novelty problem

Each time that we carry out an action on the environment, the environment and the movements are likely to be new in some of the details. A person must be able to plan a movement not previously executed in exactly the required way, such as hitting a moving squash ball. Successful movement requires the incorporation of sensory information (especially the spatial information from sight, sound, and also the sense of limb position, of movement, and of force) into movement plans, and so implies a facility that allows the translation of knowledge of the ball's location relative to the body into appropriate body movement toward the ball.

The motor plan must also allow movements to be timed. Contacting a squash ball requires the ability to predict where the ball will be at a certain time and arrange for the racquet head to arrive on time at that place with a certain momentum and travelling in the right direction. An appropriate sequence of movements must be organized, and must play out relative to the trajectory in space and time of an external object. There must be a facility that then registers and allows prediction of the future location of objects at a specific time.

Thus Figures 1.1 and 1.3 show that the motor plan has access to sensory information. It is assumed that only a few aspects of the sensory information about the environment are actually relevant to a given intended action, for example, the speed, direction, and height of the squash ball. These should suffice to predict where the racquet must be in order to contact the ball with enough force to cause it to reach the front wall of the court before it bounces a second time.

Many aspects of a new body movement will be familiar; running, stance, and the raising of the arm to swing are presumably represented as broad characteristics in a stored motor program. The novel aspect of the movement is the combination of movement parameter values that depend on the perceived movement of the ball relative to one's body, for example, the combination of a particular speed and direction of running, the height of the arm relative to the floor (ie. degree of knee flexion) at stance, and speed, direction and force of the arm movement during the racquet swing.

Even a new complex movement can be planned using old parts of a motor plan. There is behavioral evidence for a stored representation of some aspects of a motor plan for a new complex movement. Movements carried out by anatomically non-contiguous limbs tend to show similar spatial characteristics, even if the action is new to a particular limb. A writer produces a characteristic signature, regardless of whether the limb that writes is the hand, the foot, or even the head (eg. Woodworth, 1903; Merton, 1972; Raibert, 1977), and regardless of the size of the writing (eg. Hollerbach, 1978). These findings suggest that the action arises in part from a stored representation or remembered motor plan. Moreover, the less variable characteristics of an action hint at possible parameters of motor plans (eg. Vredenbregt & Koster, 1971). In light of these facts I consider the motor plan to be retrievable from memory, and to store a broad design for movement, one that could be tailored to new circumstances by changing values of the parameters of the motor plan.

1.4.4 Patterned excitation at the spinal cord

Twenty years of research have confirmed that the spinal cord generates many patterns of movement that involve alternation of limbs on the same girdle, as in swimming, or walking, and coordination of anatomically contiguous limbs, as in walking or hammering (see Grillner, 1981, for a review of locomotion). Much of the temporal patterning of movement may then be under the control of the spinal cord, if humans rely on central pattern generators as heavily as do other species, as we might assume. It should be noted that the central pattern generators referred to in the physiology literature feature oscillatory units.

1.4.5 Coordination

Limbs that move repeatedly and simultaneously tend to move at the same, or harmonically related, frequencies and maintain a stable phase relationship to each other (von Holst, 1937:1973 and 1939:1973; Klapp, 1979; Kelso, Holt, Rubin, & Kugler, 1981; Scholz and Kelso, 1989). This is true even when the limbs are anatomically non-contiguous. It is harder to tap the two index fingers in a 3:2 or 5:2 rhythm than in a 3:3 or 6:3 rhythm, even though the latter cases require more taps. From this, we can deduce that coordination of simultaneous rhythmic voluntary movements is a preferred policy of the nervous system. This argues strongly against independent control by the brain of each element in a sequence of movements and of each limb when limbs move simultaneously.

It ought to be easier to produce 3 taps with one hand and 2 with the other, rather than 3 taps with both hands, as fewer motor commands should be required. The fact that this is not so tells us that limb movements are not always planned or executed in strictly serial fashion. The brain tends to time the limbs' simultaneous movements as though there were only one pattern of timing (Kelso, Tuller & Harris, 1983; Scholz & Kelso, 1989). Even for a non-rhythmic event, the length of time to complete simultaneous reaching movements of different extents by the two hands is virtually identical (Kelso, Southard, & Goodman, 1979).

At the root of this motor synchronization should be a system that tends to organize itself. The sign of self-organization is patterned output, whether spatial, as in bees' honeycombs, or temporal, as in the interdependent levels of the rabbit and lynx populations.

It is assumed that there is an oscillatory system capable of producing patterned output which would give rise to the synchronized movements that have been observed in humans. I shall now describe such a system.

1.5 The Non-Linear Oscillatory Metaphor

The traditional framework for investigations of movement is newtonian mechanics. To illustrate this system using billiards, the displacement of a billiard ball to a desired position on a table can be brought about by the application to the ball of a particular amount of force acting in a specific direction. However, if we add another forty billiard balls to the table, moving the original billiard ball to the desired position now becomes an enormously difficult proposition. The brain must now consider interactions with many intervening billiard balls.

With very complex systems we are at a loss. We often cannot predict accurately what the weather will be in several hours, let alone tomorrow. There are simply too many factors, and their relative importance can vary as they interact. Newtonian mechanics often provides too simple a model for organizing the weather and, as I shall argue, voluntary movement. On the other hand, the weather is probably organized in a more chaotic fashion than are our voluntary movements.

I shall assume that the timing of voluntary movement is organized by a non-linear oscillatory (limit-cycle) system. This type of system would tend to produce coordinated and rhythmic movement, which a simple newtonian system would not.

The necessary properties of non-linear oscillatory operation are: oscillation at a preferred frequency in isolation, non-linear interactions between the preferred frequencies of coupled oscillators, a non-linear range of frequency for coupled oscillators, and a driving force for the oscillatory system. I shall outline each property in turn.

It should be noted from the start that my use of the non-linear oscillator is metaphorical. While oscillatory circuits do control certain types of movement, for example, flight in the locust (Wendler, 1974), it is not known whether humans feature such circuits.

1.5.1 Preferred oscillation frequency

In isolation, an oscillating system will produce signals that can be described as oscillatory if plotted with respect to time. Such a system oscillates at a preferred frequency (the property of harmonic oscillation). With regard to movement, a fish fin exhibits a characteristic frequency of undulation (eg. von Holst, 1937:1973 and 1939:1973). Humans prefer to tap their fingers within a narrow band of frequencies (Michon, 1967). This property characterizes both linear oscillators, such as tuning forks, and non-linear oscillatory systems, such as a pair of mechanical clocks hanging next to each other on a wall.

1.5.2 Non-linear interactions between oscillators

Coupled non-linear oscillators with different preferred frequencies will all oscillate simultaneously at one frequency, and/or its harmonics. This is not a property of a linear oscillator, which should maintain its preferred frequency when coupled to other linear oscillators. Some oscillatory systems that are viewed for practical purposes in everyday life as demonstrating linear oscillation, such as a mechanical clock, may be shown to behave in a non-linear fashion if coupled to another oscillator, for example, to another mechanical clock.

The principle of non-linear interaction is illustrated beautifully in von Holst's papers (1937:1973 and 1939:1973) on fin movement in fish. If the dorsal and a pectoral fin each undulate alone, each will demonstrate its unique preferred rate of undulation. If both fins are allowed to undulate simultaneously, they will operate at the same rate, which entails slowing down or speeding up of the dorsal fin.

A consequence of the joint adoption of one frequency (and/or its harmonics) by many oscillating units is that the phase of any participating oscillator relative to the phase of any other one is stable. So when a parent (a driving oscillator) pushes a child on a swing (a non-linear oscillator), the parent pushes the swing at the same point in the swing's cycle each time, just as the swing is beginning to descend from its maximum height. The relative phase of parent impulse to swing cycle is constant.

Because non-linear oscillators, taken singly or as a group, have a preferred frequency, recovery from minor imposed perturbations to a movement occurs virtually immediately. The previous frequency of oscillation will reassert itself if the perturbation is small (Tuller, Fitch & Turvey, 1982; Kelso et al., 1983). A corrected motor command from the brain would not be necessary. A non-linear oscillatory system resists minor perturbation: the joint frequency of the oscillators is stable.

1.5.3 Driving Force

The non-linear oscillators that I am discussing require energy as input and they dissipate the energy transmitted to them. Non-linear oscillators have access to a driving force, which supplies power.

A child on a playground swing (the non-linear oscillator) being pushed by a parent (a driving oscillator, or forcing function) is a good example. The parent can set the swing in motion by giving a push of sufficient force in the right direction to the swing. Provided that the parent continues to supply a push of sufficient force at the right point in the oscillation of the swing, the oscillation will be maintained.

With respect to body movement, the existence of a driving, or forcing function, must be inferred. The inference is warranted by experimental results on the arrest of movement. Von Holst (1937:1973) demonstrated that a fish fin whose undulation had been stopped externally resumed undulation at the same frequency as that of a concurrently undulating fin that had not been stopped. Moreover, the frequency of the reactivated dorsal fin differed from its preferred frequency (the frequency at which it undulated when no other fins were active). Since the fin began to undulate again, it must have been subject to a driver. Either the drive to both fins was shared, or the continuously active fin drove the late starter.

In the context of human movement, the joint frequency of tapping the index fingers of both hands implies a driver that simultaneously operates both limbs, or one limb driving the other.

1.5.4 Non-linear frequency range

There is a limited range of frequencies within which oscillation occurs. Too large a driving force sends the oscillator outside its range of oscillation. An improperly timed impulse can halt the oscillation. However, I must point out that a range of driving impulses can be tolerated in a non-linear system, as sections **1.5.2** and **1.5.3** indicated above. The parent's push can vary considerably in force without endangering the health of the child in the swing, or allowing the swing to come to a stop.

1.6 Organization Using Oscillatory Principles

A few comments about non-linear oscillatory motion are in order. First, the driving force need not be an oscillator. It could be a continuous force, like the wind ruffling the water into waves, or like gravity. Mechanical clocks can be operated by a mass under the driving force of gravity and an escapement mechanism.

Second, many different objects may comprise an oscillator system; the properties of non-linear oscillation do not inhere in mass or force, in flesh or electrical discharge, but in the nature of their combination. So, a flag flapping in the breeze may serve as an example of a non-linear oscillatory system; neither the soft cloth of the flag, nor the rigid material of the flagpole, nor the continuous breeze is in its own right oscillatory or non-linear. In an non-linear oscillatory system, there must be a source of energy to serve as driver and there must be an element that can be driven. The quality of the resultant oscillation will depend upon the nature of the force, the nature of the driven elements, and the nature of their linkage.

I assume that the motor plan is devised by the brain, and has at its disposal the means to organize voluntary movement on a cyclical basis. The movement might be patterned in an obviously oscillatory way as continuous smooth movement of a limb about a joint, or as a unidirectional partial rotation about a joint. Thus, reaching for a coffee cup could be viewed as a movement that is organized using only part of the full cycle of arm abduction and adduction.

The form of the means is not known. It is not necessary that individual independent oscillators be present in the brain. A program that can specify the appropriate amount of force at the appropriate frequency to units that can be driven could also produce oscillation.

The motor plan would probably need to specify *the limbs to be used*, thus nominating the muscle groups to be coupled, *the frequency* of the movement, which would be the speed of movement and/or the rate of repetition, the amount of *force* to be issued, or the speed and/or amplitude of movement, and the *sequence* of limb movements, or the *phase relationship* between segment movements. These parameters have been considered important by students of motor organization in the past (eg. Turvey, 1977; Schmidt, 1982a and b; Craske & Craske, 1985 and 1986).

The most relevant work on humans in this regard has been conducted by Craske and Craske (1985 and 1986). They have shown that large involuntary oscillating movements of the arms result following muscular strain. These oscillations can be transferred from a limb that has exerted muscular strain to ones that have not. This suggests, as does the demonstration of handwriting with a pen in one's foot or teeth (Raibert, 1977), that the specification of limb groupings is at a higher level of the nervous system than the used muscle. The Craskes have specifically linked the transfer of oscillation between limbs to attention, stating that directing attention to a limb can open the gate for oscillation in that limb (1986). If attention serves as a gate, then oscillatory processes may well operate at the highest levels of the nervous system.

In the first instance, the test of the nature of the organizing system should be a test of its response to patterned input, rather than the potentially fruitless search for any one of a multitude of possible forms that the oscillating system may take. If the frequency of a repeating movement can be shown to change predictably in the face of a conflicting, externally specified driving frequency that presumably addresses the brain, then it is sensible to infer that the organizing system should feature a parameter like frequency. Frequency is most usefully specified in a system which allows oscillation at a frequency, and so biasing the frequency of the repetition of a movement implies (if we wish to be most parsimonious) an organizer that follows oscillatory principles. This is the reasoning upon which the thesis' experimental hypotheses rest.

1.7 Advantages of the Non-Linear Oscillatory Metaphor

In addition to accounting for the tendency toward coordinated voluntary movement, the non-linear oscillatory metaphor offers several other advantages.

1.7.1 Reduction of degrees of freedom

The non-linear oscillatory system reduces the degrees of freedom that a motor plan must control, compared to the case of addressing each limb individually. In principle two limbs, or all the segments within one limb, could be controlled by one driver, which the motor plan could address or include. To manage the limbs in this fashion, the brain must be able to specify which limbs are to be grouped together to be treated as a unit to be driven. The terms synergy (Bernstein, 1967, p.93) and coordinative structure (eg. Turvey, 1977; Fowler, Rubin, Rumez & Turvey, 1980; Kelso et al., 1981) represent this idea. The nervous system must be able to set up a driver for segments that are not necessarily anatomically contiguous.

1.7.2 Reduced demand for storage

The tendency toward a stable frequency of oscillation by simultaneously moving limbs means that many details of timing need not be stored separately for each limb; instead a basic frequency and the pattern of distribution among the limbs of its harmonics and their phase relations could be stored.

1.7.3 Accounting for patterned excitation at the spinal cord

Following a non-linear oscillatory model, one would expect rhythmic electrical patterns to be generated within the human nervous system, and these patterns to be associated with flexion and extension movements of limbs, as has been shown to be true for various animals (see Grillner, 1981). Nonetheless, it would be premature to claim that patterns in humans must be generated at the brain stem or spinal cord, or that the oscillation must occur in set locations or the oscillating units be formed from specific materials. The nervous system must employ some combination of command structure and mechanism that is in nature a non-linear oscillatory system.

1.8 The Role of Kinesthetic Afference in Organizing Movement

1.8.1 Accommodating novelty

The non-linear oscillator metaphor can only be valid if it allows sensory information a place in the drafting and monitoring of the motor plan. Otherwise, the motor plan cannot fulfil the animal's purpose, for it will not be able to accommodate novel environmental circumstances (see section **1.4.3**). One would have very little hope of contacting a fast moving squash ball and returning it to the front wall without knowing where one's racquet arm is relative to the body.

An oscillatory model need not stand in opposition to a motor plan that draws on sensory information. It needs to be remembered that much of the research on oscillatory systems that control movement has been carried out on deafferented animals (eg. Polit & Bizzi, 1978; Shik & Orlovsky, 1976). The capacity to organize leg movement (eg. Lashley, 1917) or pointing (eg. Bizzi, Polit & Morasso, 1976) or walking (eg. Grillner, 1981) and chewing (eg. Luschei & Goldberg, 1981) in the absence of sensory input does not mean that an oscillator model should not, in normal circumstances, show movement planning drawing on sensory information. Indeed, in recent work, the subtle expression and substantial nature of sensory influence in motor behavior has been stressed (eg. Baessler, 1986; Lund & Enomoto, 1988; Rossignol et al., 1988; Katz & Harris-Warrick, 1990).

1.8.2 Spatial patterns

The non-linear oscillatory metaphor allows many spatial parameters of the motor plan to have stable values during a repeated movement; these may or may not affect the organization of timing, which is where the non-linear oscillator metaphor would most clearly be relevant. So it would be plausible for a motor plan to specify spatial parameter values for the overall direction and amplitude (or force) of a set of movements, like those that comprise walking. However, the relative speed and duration of the composite movements that yield the desired translation of the body in space, such as knee flexion and extension, would be the realm in which the non-linear oscillator metaphor should most obviously apply.

Work on spatial patterning also supports the metaphor. It is easiest to sign one's name with the non-preferred hand in mirror image if it is done simultaneously with the preferred hand signing normally (Woodworth, 1903), rather than in isolation. The programming of novel spatial manoeuvres can be facilitated, not impeded, by relevant concurrent movement of other limbs.

1.9 Motor Programs vs the Non-Linear Oscillator Metaphor

In recent years, movement has been modelled as arising from a program, such as a computer follows when operating (eg. Adams, 1977; Schmidt, 1982). If there are to be invariant parameters for some movements, like handwriting, then there is a theoretical place for a motor program that is stored in memory, recalled when needed, and invoked. A motor plan might well use some commands in sequence (a motor program), and invoke oscillator control for the relative timing of movements (via oscillation generators), for example.

Having said that, it nevertheless must be said that the sequence of computer type commands cannot substitute theoretically for organizing with a non-linear oscillator system. Devices that induce repetition, for example, loops (in models of motor organization that exclusively feature programs), issue commands continuously, instead of organizing at the outset an appropriate system of units that can produce an oscillating signal, and setting the system going.

The oscillator view is economical. As oscillators can be driven by properly timed impulses, commands for patterned movement need not be reissued by the brain for every instance of repetition. All that is needed is that the brain arrange continuous drive or trigger an oscillator that can drive subordinate oscillator groups.

Lastly, it makes sense that movements that require fewer organizational resources should be easier to complete successfully and take less time to carry out (implied by Kahneman, Ben-Ishai & Lotan, 1973). From the programming point of view, it would be expected that a movement carried out by two anatomically non-contiguous limbs should arise from a more complex program than that which directs one limb in isolation, and should be more difficult to perform. This argument is especially cogent if the movement is novel for the second limb, as closer monitoring should be required. The ease with which people write their name in mirror writing with the unpractised hand, provided that it is done in phase with the preferred hand signing normally, directly counters the strong version of the computer program view.

In sum, there are two views: the motor program view, in which mold numerous modern and traditional theoretical treatments of speech production are cast (eg. MacNeilage, 1970; Kent & Minifie, 1977; eg. Dell, 1988) and the oscillator view (Luschei & Goldberg, 1981; Rossignol et al., 1988), of which the mass-spring model (Bizzi et al., 1976; Tye, Zimmerman & Kelso, 1983) can be considered a sub-type. Currently, in the field of movement study, the two views are melding; motor programs (eg. Schmidt & McGown, 1980) and central pattern generators (Grillner, 1981; Cohen et al., 1988) are both being incorporated into the same motor plan (eg. Schmidt, 1982).

The current versions of the oscillator view, particularly the mass-spring approach, do not elucidate a role for sensory information at the movement planning stage (eg. Bizzi et al., 1976;

Kelso, Saltzman & Tuller, 1986a and b), and the participation of kinesthetic information in organizing movement has been overlooked. The concentration of work during the last 20 years on deafferented animals has glossed over the chasm between the intact animal (a complete system) and a partly destroyed one (a disrupted system).

Clearly, we want mainly to know how the <u>intact</u> animal works. This aim is beginning to be acknowledged (eg. Rossignol et al., 1988). Work on invertebrate movements shows that a non-linear oscillatory system can use sensory information (eg. Katz & Harris-Warwick, 1990; see section **1.8**).

1.10 Conclusions: the Non-Linear Oscillator Metaphor

The non-linear oscillator system serves as a suitable metaphor for movement organization. The instructions for movement from the brain must either be couched in terms that would elicit non-linear oscillatory control, or be converted into these terms.

Sufficient evidence exists that complex repeated movement is under control that is in nature that of a non-linear oscillatory system. It can be inferred that voluntary movement of other kinds could arise from oscillatory operation too (eg. Kelso et al., 1979; see Craske & Craske, 1986). This could mean that the oscillator is a valid metaphor for the whole class of voluntary movement. Its reach is unknown; further experimentation will eventually answer that question.

1.11 The Movements under Study: Speech and Finger Movements

Speech has traditionally been studied as a communication system rather than as patterned voluntary body movement. In contrast, I propose to place speech at the end of a continuum of types of complex voluntary movement and to study it in that context. I am concerned with the influence of kinesthesis upon speech movements, and not with the communicative function of fluent speech. I also investigate finger movements, so as to have a basis for comparing speech movements to other body movements.

The types of movements that I shall investigate are voluntary. Limb and speech movements probably include preliminary and reflex postural components. In addition, they may be more or less consciously attended.

1.12.1 Slow vs ballistic movement

Researchers have generally conducted experiments using one type of movement, for example, slow, voluntary movements, like reaching for a light switch, or fast ballistic movements, like dart throwing.

The border between the two types of movement has been set by reaction time, which is about 130 ms (Keele, 1986; but see Smith & Bowen, 1980: 100 ms and Abbs et al., 1984: 50 to 70 ms), minimally. The reason that the distinction between slow and ballistic movement has traditionally been viewed as being important is that slow (more than 130 ms in duration) movement should be corrigible by cortically mediated feedback as the movement progresses, while ballistic movement should not be open to such feedback (see Dickenson, 1976). This distinction may not be important, given the availability of fast feedback that corrects movement, probably before being given conscious form (eg. Shik & Orlovsky, 1976; Folkins & Abbs, 1977).

English speech features both ballistic gestures, mainly for

1.12 Voluntary Movement

Voluntary movements are consciously willed, and may be contrasted with involuntary movements, which one performs without intending to, and imposed movements, which are imposed upon one's body by an external agent. The involvement of consciousness in voluntary movement can be minimal, for example when walking home, deep in thought about some abstract problem. Patterns of movement that are well-learned need less conscious attention to be successfully carried out (implied by Kahneman et al., 1973; see Abbs et al., 1984).

Consciousness has been used to distinguish theoretically different types of movement (reflex, voluntary, involuntary movement), but their organization is not separate. At the disposal of the conscious movement planner lie mechanisms like the alpha-gamma motor loop, traditionally associated with reflexes. Many voluntary movements involve movements that may not be consciously purposeful (Abbs et al., 1984). Posture is firmly set, without attracting the actor's attention, before the consciously intended movement is begun (Cordo & Nashner, 1982; Nashner & Forssberg, 1986). Thus, reflexes and preparatory movements, of which we are not normally consciously aware, can occur as part of one voluntary action.

consonant and unstressed vowel articulation, and slower gestures, for stressed vowels. Stressed vowels can resemble postures that are gradually reached (100 to 250 ms duration), while the English stop consonants feature plosive ballistic gestures of the jaws, lips, tongue or glottis (10 to 50 ms, commonly).

Finger movements may be either ballistic or slower, depending upon the purpose of the movement or the decision of the subject.

1.13 Hypotheses

First the existence of kinesthesis for the speech organs needs to be established, for the knowledge of the position, movement and shape of the speech organs is logically prerequisite to planning their movement, as argued generally in section **1.3**. If kinesthesis exists for the tongue then a major sensory requirement of the motor plan (see section **1.3**) would be met. Further, that would suggest that speech movements could be organized similarly to other body movements.

Hypothesis 1: Kinesthesis in speech

Kinesthetic sensations should be available for organizing speech movements.

As speech does not require visual guidance, the most relevant sensory information before speech is issued should be kinesthetic information, that is, information about articulator shape, size, position, and current movement speed and force. Traditionally, sensing only position, movement and force has interested researchers inquiring about limb movement, but as one of the speech articulators is the very flexible tongue, sensing shape and size should also fall under the umbrella of kinesthesis.

Second, following the non-linear oscillatory metaphor, I expect that repeated voluntary movement can be driven by a rhythmic stimulus, here, kinesthetic information. Entrainment (that is, adoption of a concurrent rhythm; see Chapter **8**, section **8.13** for full definition, and Chapter **9** for the null hypotheses about entrainment), induced via kinesthesis, would at once support the non-linear oscillatory and the sensory aspects of the theoretical view expounded here.

Hypothesis 2: Entrainment of limb movement

Rhythmic limb movements tend to entrain to a kinesthetic rhythm.

As I argue that speech movements are organized similarly to other types of body movement, what can be hypothesized about body movement should also apply to speech movements. Thus:

Hypothesis 3: Entrainment of speech movements

Speech movements tend to entrain to a kinesthetic rhythm.

There is already evidence that speech is affected by certain kinds of sensory rhythms, for example auditory rhythms (eg. delayed auditory feedback: Katz & Lackner, 1977; tracking tones: Klapp, 1979). I suspect that any conflicting sensory rhythm in the monitoring channel, (for example, channels such as hearing or vision) of the produced movement will tend to serve as a driver (see Chapter **8**, section **8.4** for arguments).

Further to hypothesis 2, researchers have observed certain values of phase: 0^0, 90^0, 180^0, and 270^0 (eg. Browman & Goldstein, 1986; Scholz & Kelso, 1989 and 1990). In systems of coupled non-linear oscillators these values of phase of driver movement relative to that of the driven object are common. Various researchers have shown that these phase relationships mark the simultaneous movement of the limbs (eg. Kelso et al., 1981: 0° and 180°; Craske & Craske, 1986: 0°, 45°, 90°, 135°, and 180°; Scholz & Kelso, 1989: 0° and 180°). I wondered whether these phase values would also mark entrained speech and limb movements. There is no obvious theoretical reason for expecting these phase values to characterize the organization of speech movements.

I wish to consider a strong test of entrainment, namely, that entrainment of the limbs to a rhythm arises without prompting the subject. Therefore:

Hypothesis 4: Strength of tendency to entrain

> Subjects will tend to entrain their movements to those of a rhythmic kinesthetic stimulus without having been explicitly instructed to entrain to it.

1.14 Further Implications

If entrainment does occur spontaneously, the question arises whether the brain catalogues incoming sensory information in the same way as it organizes outgoing motor commands. It would be efficient for the methods of organizing incoming and outgoing information to be similar or identical. If it could be shown that the oscillatory character of coordinated movement also marks the interpretation of afferent information, the reach of oscillatory control would be enhanced.

Entrainment may well be induced by certain qualities of the sensory stimulus rhythm. For example, the organ addressed by the kinesthetic rhythm may prove important: the skin, the muscles, and the tendons. These questions are new and are discussed at greater length in Chapter 8.

1.15 Concluding Remarks

In order to liken speech to limb movement, it is essential to show that there is common sensory ground, that is, a faculty for kinesthetic mapping. Thus, the hypothesis about kinesthesis in speech is fundamental. Without knowing what sensory information about the speech articulators is available, it would not be sensible to investigate the bases for non-auditory sensory rhythms. In consequence, the next 6 chapters of the thesis consider position sense in the tongue (Chapters **2** to **7**).

Exposition of entrainment will confirm that limb and speech movements are organized in accordance with non-linear oscillatory principles. Moreover, it will indicate that the oscillatory principles are relevant for the organization of sensory input. Such a demonstration would proclaim that the oscillator has a much deeper meaning for the organization of behavior than has yet been granted. Chapters **8** to **11** examine the hypotheses about entrainment of speech and limb movement and the nature of the stimulus that induces entrainment. The thesis is concluded by a general discussion in Chapter **12**.

CHAPTER 2

POSITION SENSE IN THE TONGUE: INTRODUCTION

An animal must know where its limbs are located relative to its body if it is to be able to act in any purposeful way upon its environment. When we idly scratch an itchy insect bite on our back, we are relying upon this knowledge, or position sense; we know both the location of the irritation upon the skin on our body surface, and the location, relative to the trunk, of the fingers that will relieve the itch.

This sensory capacity is crucial to normal motor function. Chapter 1 argued that accomplishing a spatial task efficiently requires that the motor plan have access to knowledge of the current position of body parts. Although vision can stand in for kinesthetic sensation for activities in our visual field, the logical need for an intrinsic sense of position in movable body parts is not vitiated. Vision cannot substitute for kinesthesis for the tongue, and so the existence of accurate position sense for the speech articulators is critical.

It follows from the above that it is inconceivable that the articulators could be directed with the precision that speech extorts if we could not sense its position, particularly when we learn to produce new speech sounds. This tenet has been recognized by numerous researchers in speech-related fields (eg. MacNeilage, 1970; Perkell, 1979; Lowe, 1981; Sheldon & Strange, 1982; Starkweather, 1983).

While there is evidence that speech production is not likely to be organized as a series of commands to muscles to move articulators to particular points in space (eg. Folkins & Abbs, 1975), a set of spatial-acoustic mappings is logically required at some level of speech production. The correspondences between the shape and volume of the vocal tract and the sound that results from the different vocal tract configurations must be known, if one is to produce speech sounds reliably. Theories of speech production that propose that motor commands address higher-level structures than the muscles, namely coordinative structures, must ultimately refer to a spatial-acoustic map. This must be true, even though the representation of space by the motor commands might be couched in terms that do not refer directly to spatial targets that must be contacted, or to particular organ postures that must be adopted.

2.1 Definition of Position Sense

There is a host of sensations that accompany movement and the adoption of a posture. As yet no taxonomy of such sensations has been more than sketchily drafted; it is rare to see even a skeletal delimitation of the sense. I accept that most published work does not consider separately the abilities to sense movement, speed and extent of movement, and resistance to movement (but see Woodworth, 1903). A good question is: which sensations are the primitives, and which the derived, or can the brain create them all with facility and precision (in which case attention might choose which is temporarily to be the first among equals) ?

Recently, researchers have shown that a sense of static position and a sense of movement are available for the finger, the knee and the ankle joints (eg. Horch et al., 1975; Clark et al., 1979; Clark et al, 1986; Taylor & McCloskey, 1990; Ferrell & Craske, in press). I expect that these sensations should also be available for the speech articulators, if the motor plans for speech and limb movement rely on the same kind of sensory matrix.

I have chosen to look at what is likely to be the simplest case: sensing static position. The term position means, in my usage, the place occupied. The nature of the sensation of segment position remains ambiguous. It is possible that position sense is a derivative of information arising from movement sensations, or vice versa, as indicated in section 1.2.2 in Chapter 1. As much research on kinesthesis silently assumes that the important capacity is sensing position (eg. Gelfan & Carter, 1967; Goodwin et al., 1972), I shall concern myself with sensing static position, remembering that other sensations may supercede or generate a sense of position.

2.1.1 Past work on movement and position sense

When exploring position sense, researchers have usually tested slow movements, that is, those lasting longer than 100 ms (eg. Helmholtz, 1867/1925; Mach, 1886/1959; Goldscheider, 1889 and 1898; Goodwin et al., 1972; Clark et al., 1985). Slower movement allows time for kinesthetic sensation arising from the movement to be registered at the cortex, affording subjects whose task is to point their limb the opportunity to check kinesthetically the intended limb position against the achieved limb position. Likewise, I shall test fairly slow movements of the speech articulators.

2.2 The Articulator: The Tongue

Many segments participate in speech, and of these one of the most important and most mobile is the tongue. As it is able to move in three dimensions, curl and change shape, it is of interest to students of movement; within the reach from the tongue's root (about 80 mm at rest), the tongue tip can occupy at will virtually any place within the buccal cavity and between the lips. This freedom of deliberate movement about an anchor of flesh is unique on the human body. If ever a sense of position were an advantage, it should be so for the tongue, which can assume so many postures. Moreover, speech demands some of the finest movements in the body's repertoire. I was interested to show that the theoretically requisite lingual position sense indeed existed and was precise.

2.2.1 Extrapolation from other organs to the tongue

What we know about position sense generally is based largely on investigations of limbs, which are rigid segments, and of the eye, which is a system that bears only one load. Extrapolation from position sense in the limb to that of the tongue must be embarked upon with care. Unlike the limb, the tongue is not a constant length and has no joint. Unlike the eye, the tongue bears varying loads. The tongue is unlike the limb and eye in structure: it is a muscular hydrostat. That is, it changes shape and position (relative to the head) by squeezing fluid-filled cells of constant volume (Smith & Kier, 1989). As both structure and function of the tongue are different from those of limb and eye, I was concerned to discover the extent to which position sense might differ in these different kinds of moveable organs.

2.2.2 What is known about lingual position sense

There is a long-standing controversy in the literature about the existence of lingual position sense. Some have claimed that it does not exist for the passively moved tongue (Goldscheider, 1898; Merton, 1964) or is weakly present (Carleton, 1938). Others have accepted or implied that there is a role for kinesthesis in speech production (eg. MacNeilage, 1970; Borden, 1979; Sheldon & Strange, 1982; Starkweather, 1983).

Originally, it was thought that the tongue did not have position sense (Goldscheider, 1898). The mucosa of the tongue were thought to sense touch, but the existence of a muscular sense of position was denied (Carleton, 1938). Her finding, that the position of the human tongue was not sensed well under anesthesia of the mucosa, was refuted by Adatia and Gehring (1971), who found that eleven of twelve subjects whose lingual nerves had been blocked with anesthetic (lignocaine) could sense the direction in which their tongues were moved by an external agent (see below, section **2.3.2**). This indicates clearly that lingual position sense exists and is not mediated purely by the mucosa.

Recently, Siegel and Hanlon (1983) conducted a distance estimation experiment using the tongue which implied very clearly that lingual kinesthesis (movement sense) was available and precise for the actively moved tongue, with errors in judging distance across the palate of less than 1 mm (calculated from their results). In sum, recent work suggests that, at least for the voluntarily moved tongue, change in position is detected. However, it must be noted that these last two experiments do not tell us directly about sensing position.

2.3 Sources of Position Sense

2.3.1 Sources of positional information in the limb and eye

Over the years, views about the sources of kinesthetic sensation have swung back and forth. During the years when the general opinion was that joint receptors conveyed positional information (post Sherrington to Goodwin et al., 1972), it would not have been conventional to suppose that the tongue's position could be sensed, as the tongue has no joint.

As position sense that draws on afference from muscular receptors now is an orthodox idea again, it is time to ask whether lingual position can be sensed. How position is sensed is a question that can be partly answered by the demonstration of the existence of position sense in the tongue. Obviously, if lingual position sense exists, joint receptors are not the exclusive mediators of kinesthetic sensation for the body.

The sources of kinesthesis in the limb include afference from the spindle receptors in the limb muscles (Goodwin et al., 1972; Craske, 1977; Clark et al., 1985), the Golgi tendon organs (McCloskey, 1978; Proske, 1979), and the skin over the limbs (Clark et al., 1986), as represented in Figure **1.2** of Chapter **1**. Joint receptors in the limbs, which might supply kinesthetic information (Ferrell & Smith, 1988) are not relevant for the tongue. Also, various researchers have put forward sound arguments for a corollary discharge that must contribute to kinesthesis (Sperry, 1950; von Holst & Mittelstaedt, 1950/1973;

McCloskey & Torda, 1975; McCloskey, 1978 and 1981; Gandevia, 1982; Matthews, 1982).

2.3.2 Sources of positional information in the tongue

The tongue shares certain features with the limbs and eyes. Like limb muscle, it is richly innervated with spindles (Cooper, 1953). Anatomical investigators have consistently maintained that the spindles in the tongue muscles could relay the tongue's position (Langworthy, 1924; Tarkhan, 1936; Cooper, 1953; Bowman, 1971).

Nonetheless, the view that tongue position is not strongly perceptible, except via the mucosa, remains widespread (eg. Merton, 1964), due perhaps partly to the pre-1972 view that muscular receptors do not convey positional information, perhaps also to papers on oral sensory deprivation that could not definitively estimate the separate contributions to lingual position sense of elements other than skin, and perhaps because sensation does not appear to be necessary for intelligible speech production in the short term.

It should be noted that the afferent pathways from the spindles of the tongue to the brain have not been determined in detail (Lowe, 1981); the most straightforward possibilities are the hypoglossal (XII), trigeminal (lingual branch) (V), and glossopharyngeal (IX) nerves (Carleton, 1938). Recent work (eg. Adatia & Gehring, 1971; Lowe, 1981) suggests that the hypoglossal nerve carries afferent information from the human lingual spindles, but that information about touch from the mucosa may travel via the lingual nerve. Thus, unless all three of these cranial nerves have been blocked with anesthetic, only the loss of the sense of touch may be investigated in definite fashion. No position sense experiment, to my knowledge, has involved a nerve block of all three cranial nerves in humans.

Gammon, Smith, Daniloff & Kim (1971), Scott & Ringel (1971), and Ringel & Steer (1963) could not judge the role of the muscles and corollary discharge in sensing tongue position because they could not be certain of which elements their nerve block had disabled, and in any case they did not block branches of the hypoglossal nerve. Putnam and Ringel (1976) did allot a role to the spindles in conveying position sense, but inexplicably remarked that the resulting proprioceptive sensation was not available to consciousness.

Weddell, Harpman, Lambley, and Young (1940) claimed to have eliminated proprioceptive sensation in the human tongue by infiltrating branches of the trigeminal nerve with novocaine. As the hypoglossal nerve was not blocked (see above), this is not a justifiable claim. Further, their tests for proprioception on their human subjects are not described, so it is not possible to judge what types of kinesthetic sensation were diminished or lost. The deterioration in speech production which they noted was similar to that associated with the loss of tactile sensation alone (eg. results obtained by Ringel & Steer, 1963; Gammon et al., 1971; Scott & Ringel, 1971). The benefit of the doubt has fallen to the skin sources as potential sources of position sense in speech production. Generally, the muscles and tendons have not received due consideration.

If the joint receptors play a significant role in kinesthesis in the limbs, it can be expected that under some circumstances our sense of tongue position will differ in some respects from kinesthesis in the limbs, since the tongue has no joint.

Next to nothing is known about the contribution that tendon organs in the tongue might make to position sense. However, it is worth keeping in mind their supposed role in sensing limb position, for they may well serve in the tongue too, particularly for sensing resistance to movement.

The skin of the tongue is highly sensitive and could signal tongue position, either at contact with structures, such as the teeth, or following deformation of the mucosa, for example, following stretch of the tongue. For the tongue, a meaningful contribution from taction seems very likely. A precise sense of contact is required for the production of consonants such as /s/ as opposed to /š/. This can be inferred from the minor blurring of the distinctions between various consonants when the oral cavity and tongue surface are anesthetized (Putnam & Ringel, 1976).

2.3.3 Summary: sources of lingual position sense

While anesthesia of the skin, joint or muscle spindle receptors reduces kinesthetic sensitivity (Clark et al., 1985; Clark et al., 1986), the relative contributions of each source vary with the joint or limb investigated and the experimental procedure (eg. McCloskey, 1978; Clark et al., 1979). With respect to the tongue, work on the effect of anesthesia of the elements other than the mucosa in the oral cavity has proved inconclusive due to doubts about which elements the anesthetic blocked. In sum, anesthesia of the mucosa of the tongue might reduce kinesthetic sensitivity in a minor way, but if tongue position is sensed similarly to limb position, we should expect muscular and tendon afference and a knowledge of efference to suffice to calculate tongue position.

A contrary stance to the above would be to argue that for the tongue, the validity of position information from spindles is uncertain. The tongue's capacity to change shape could mean that a knowledge of muscle length might not suffice to convey tongue tip position very well, for the organ can bend and curl, flatten and shorten. On the other hand, the capacity to bear a varying load (the bolus of food) could mean that spindle afference might need to carry more information about tongue position than is the case for the limb, since there is no joint in the tongue to provide positional information that is untainted by the exertion of force.

2.4 General Hypotheses: Lingual Position Sense

I wished to investigate position sense in the tongue. Based on the above, my hypotheses were:

a. The position of the tongue can be sensed.

b. Sensing lingual position would be as accurate as sensing limb position.

c. The contributors to lingual position sense would overlap with those that serve limb and eye position sense, namely muscles, tendons, corollary discharge and skin.

Contrary to previous research, I expected that the mucosa of the tongue would not be wholly responsible for furnishing lingual position sense.

2.5 General Methods

Position sense in the limb and eye has been investigated in intact animals using several methods. The experimental task commonly requires the subject to point at a target with a treated limb, or to indicate the treated limb's perceived position. There are various types of treatment, for example, the administration of anesthetic to the limb, loading the limb with a weight, or imposition of movement on the limb. Thus one attempts to monitor the perceived limb position during or after a narrow range of treatment conditions. I used the above methods and sought to compare my results to what is already known about the tongue, and about the eye and limb.

I wished to use direct measurement to assess the sense of tongue position and to discover whether a bias could be induced in the judgment of tongue position similar to the biases observed in association with muscular strain in the eye, and under certain circumstances of strain in the limb.

2.5.1 The pointing task

Traditionally, research on position sense has exploited placement tasks, for example, pointing one finger at a target or matching one finger's position to the sensed position of another (eg. Slinger & Horsley, 1906; Merton, 1961). I used the task of pointing the tongue at an extension of the finger tip.

Such tasks give a mismatch, or combined error: in traditional experiments it has been assumed that the position of the pointing limb and the position of the target limb are each known with a certain error (eg. Merton, 1961).

The positions of a target limb and that of the indicator limb or eye are known with about 4° of error (see Goldscheider, 1898 (wrist); Slinger & Horsley, 1906 (arm); Merton, 1961 (finger and eye); McCloskey, 1973 (elbow); Horch et al., 1975 (knee); Clark et al., 1985 (ankle);). If this error is partitioned equally between target and indicator, then the position of <u>each</u> organ is presumably known with about 2° of error.

<u>2.5.1.1 Hypotheses addressed by pointing tasks</u>.

The hypothesis that the position of the tongue can be sensed ((a) above) can be addressed by a task where subjects point their tongue tip at a kinesthetically defined target, the finger tip. If the tongue tip position corresponds reliably to finger tip position, then it is likely that the tongue's position can be sensed.

I can also verify the accuracy of lingual position sense (hypothesis (b) above) with a pointing task. The error of tongue placement, in degrees of lingual angle, should be similar to the errors in limb and eye placement recorded in the literature, if tongue position is sensed similarly to limb and eye position.

With respect to the third hypothesis, the contribution of the skin to lingual position sense can be separated out by comparing judgment of tongue position during surface anesthesia of the tongue to judgment in absence of anesthetic treatment.

2.5.2 The loading treatment

In other studies of sensory systems, the after-effect of effort or strain against a load has been a useful tool in inferring underlying process. It allows comparison with after-effects in other organs, since both eye and limb are known to exhibit good position sense under a range of conditions, but to exhibit marked differences in the accuracy of position sense under load. This has in turn led to hypotheses about the differing sources of kinesthesis in limb and eye.

2.5.2.1 Position sense following loading.

The eye, like the tongue, has no joint, and so the potential sources of kinesthetic sensation are fewer than those available in the limb. Under load, misjudgments of eye position, in error by as much as 90^{0}, occurred (Skavenski, Haddad & Steinman, 1972). Errors of this magnitude have never been observed in the loaded limb, even with muscle vibration. It is possible that the magnitude of the error for the eye is due to the lack of calibration of eye position for the amount of force exerted to turn the eye, or because it has no joint receptors.

I was interested to know whether such large effects might also be associated with loading the tongue. Like the eye, it has no joint, but like the limb it is accustomed to bearing a load.

The evidence that effortful muscular work influences perceived joint angle or judged distance between fingers is not immediately compelling, in view of the intimate involvement of muscle in position sense. Under normal circumstances, the muscles must increase their tension to overcome a force, for example, gravity, or to maintain a limb's position, or to move the limb and a mass from one position to another. There is plenty of research to show that exerted force and adopted limb position are normally sensed accurately and independently (see Rymer & D'Almeida, 1980), although the sense of effort may influence the perception of position (see McCloskey, 1981).

There is nonetheless some evidence to suggest that under special conditions muscular strain can be associated with misjudgments of position. Misjudging the position of the arm may depend on the type of strain and expectations about the work to be accomplished by strain. Experiments which require the exertion of force but which do not allow calibration of that force against position are rather unnatural. While Watson, Colebatch & McCloskey's subjects (1984) were allowed to check visually their finger positioning frequently, it is not clear that they were allowed at any time to check visually the position of their finger tip while straining against the springs. To the extent that position sense is a muscular phenomenon, it is not surprising that errors in judging position occur when subjects have not been given the chance to calibrate the trade-off between afference due to force and that due to position.

The bias in sensing position appears to depend upon the level of previous strain, to judge from the work of Watson et al. (1984). The reliable misjudgment of position may well represent an attempt to deduce the ultimate position using as a relevant, but misleading, parameter the force exerted to move the limb into position. Thus the estimate of the work to be accomplished could be argued to bias the subjects' sense of the extent of movement, and ultimately of position. Similar effects to those of Watson et al. (1984) have been noted in studies of the effect of load on the sensed extent of movement (eg. Roland & Ladegaard-Pedersen, 1977; Rymer & D'Almeida, 1980).

This field of research employs several types of experimental procedure. In the first instance, the limb or eye makes a large voluntary movement. Judgments of its ultimate position after termination of movement reveal that the limb or eye is perceived to occupy a position further in the direction opposite to the direction of previous deviation than is correct (Hoff & Schilder, 1925; Howard & Templeton, 1966; Park, 1969; Craske & Crawshaw, 1974a; Craske, Crawshaw & Heron, 1975).

In the second instance, a limb position is maintained against a weight. Its position is indicated during strain as being too far in the direction opposite to the one in which the limb is straining (McCloskey, 1973). Perhaps most directly relevant to work on the tongue is the large, but directionally unspecified, bias in sensed eye position during loading observed by Skavenski et al. (1972).

Related positional biases are displayed in the illusion of impact and the series effects outlined by Hollingworth (1909). Howard & Templeton (1966) have speculated that persistence of muscular tension, sensory adaptation, and/or central processes might each have a role to play. More recently, spindle response facilitation, motoneuronal pool potentiation and muscle fiber twitch potentiation have been proposed as contributors to the bias (Hutton, Enoka & Suzuki, 1984; Gregory, Morgan & Proske, 1988).

The spindles in a muscle that has just borne a load continue to discharge for at least 50 seconds (humans: Hutton et al., 1984) to several minutes (other animals: Hutton, Smith & Eldred, 1973). It is not fully clear how the accompanying misinterpretation of position arises: whether the spindles alone are affected, whether the corollary discharge associated with willed movements after relief from the load might also contribute to the bias, and to what extent afferents other than the spindles might be affected (Hutton et al., 1973).

The evidence for these biases is drawn from work on eyes and limbs; from the current state of knowledge about position sense the inference to be made is that these effects arise at least in part from biases in afferent information from the muscles. Consequently, to the extent that the tongue uses kinesthetic mechanisms that are based on muscle, we would expect to find normally good position sense in the tongue that can be biased by previous loading.

2.5.2.2 Hypotheses addressed by the loading treatment.

Evidence for the first hypothesis, that lingual position sense exists, will be forthcoming if, before strain, subjects are able to place their tongue tip in a given location consistently. A further indication that it exists would be that, after strain, the tongue tip is placed in a new location, showing that the sense of its position has been biased by loading.

The sources of lingual position sense can be partly disentangled by investigating the after-effect of loading. As the after-effect in the limb is considered to have a mainly muscular cause, its presence in the tongue would suggest that the tongue muscle contributes to lingual position sense in some way. Given the past emphasis on the role of the skin by those who study speech, it will be interesting to see whether the skin contributes positional information that can override a muscular bias in the calculation by the brain of tongue position. A study of the after-effect of strain in the presence and absence of anesthetic should treat the third hypothesis, for it should reveal whether muscular afference can convey positional information.

2.6 Conclusion

Chapters **3** to **6** contain the reports of experiments based on the hypotheses described above. The object of investigation was the sense of the tongue's position. I wished to test the accuracy of the sense, for the sense exists inasmuch as it is demonstrably accurate. Two spatial dimensions explicitly provided the testing arenas, the horizontal (Chapters **3** and **5**), and the vertical (Chapters **4** and **5**).

I also wished to obtain some insights about the sources of lingual position sense from the experiments. In consequence, the accuracy of position sense was explored when the skin could contribute information and when it could not, due to anesthesia (Chapters **3**, **4**, **5**, and **6**). The accuracy of lingual position sense following movement of the tongue imposed by an external agent (Chapter **5**) and following active tongue movement (Chapters **3**, **4**, and **6**) were tested. The muscles could be presumed to signal position less accurately when relaxed (see Craske & Crawshaw, 1975a). Also, position sense was tested under conditions when positional information from the muscles should be biased (after strain, Chapter **6**), and when it should not be (chapters **3**, **4** and **5**).

CHAPTER 3

HORIZONTAL POSITION SENSE IN THE TONGUE

People should be able to perceive the actively adopted position of their tongue. This chapter investigates the perception of tongue position in a horizontal plane.

If the tongue's position could be perceived, I expected that it would be most accurately known for a region which had been mapped in detail, calibrated by physical contact, and whose mapping was most continuously updated. In a region still within the bounds of the sensory map of the tongue's range, but less familiar to the tongue, the mapping might be coarse, or out of date more often. Imprecise and inaccurate mapping could be the costs of fleeting acquaintance with a space.

In fact, whether the accuracy of position sense extrapolates over a relatively unfamiliar space is not known. Accordingly, two regions, one familiar to the tongue (inside the mouth), and one that was held to be less familiar to the tongue (outside the mouth beyond the lower lip, where the tongue also moves purposefully (to lick the lips, for example)) were the experimental spaces.

People should be able to move their tongue tip deliberately to a given point in these spaces. I decided to test this with pointing tasks. If the tongue can be pointed accurately at an object, such as a fingertip, or a

2. Subjects should be able to perceive the position of their tongue when it points at targets both inside and outside the mouth. Perception of tongue position should be more accurate inside the mouth, as I presume that the sensory map for this area is more thoroughly and continuously calibrated than that for the area outside the mouth.

The targets for the positioning tasks were the location of stimulation on the gingiva at the top three gaps between the upper teeth and three positions, indicated by the subject's upright finger, along a horizontal wire guide beyond the lower lip.

3.1 Method

The experiment measured subjects' error in pointing at targets with their tongue. The two independent variables were the experimental region: inside/outside the mouth, and availability of tactile information from the surface of the tongue: anesthesia/no anesthesia.

To preclude improvement due to the subjects' receiving information about their success at the task, a barrier was introduced between the target and the tongue tip, preventing relevant contact.

3.1.1 Subjects

Two female and one male paid, and one female and one male unpaid subjects aged between 22 and 50 with no history of speech impairment or tooth, then it can be inferred that the positions of the target object and the pointing tongue are known.

Such tasks give a mismatch, or combined error (eg. Merton, 1961; see section **2.5.1**). There is as yet no basis for dividing this error unequally between the pointer and the target. It seemed reasonable to assume that each segment, tongue and finger tip, is equally in error, until we have evidence otherwise.

If tongue position is perceived as accurately as is limb position, then the combined error (for both tongue and fingertip) should be no larger than the combined errors reported for positioning tasks in the literature. Further, the error associated with the finger pointing task here, after partitioning the compound error, should not be larger than the error that can be ascribed to it (after equipartition of the combined error) in reports of pointing at seen targets (eg., between 2° and 5°: Merton, 1961).

I was also interested to know whether the skin of the tongue was vital to conveying position sense. To test this, the pointing tasks were performed in both the presence and absence of anesthesia of the mucosa. From the above arguments the expectations were that:

1. Subjects should be able to perceive the position of their tongue, and should therefore be able voluntarily to point their tongue accurately at kinesthetically defined targets, both in the presence and absence of tactile information from the surface of the tongue.

motor disorder participated. Only the two unpaid subjects (S4 and S5) participated in the anesthetic conditions. The three paid subjects had no opportunity to practice the tasks before the experiment.

3.1.2 Materials

In all experimental conditions, a headrest incorporating a padded nose bar, chin rest and head strap was used to keep the subject's head in position (see Figure **3.1**).

The fiducial mark on the tongue was a flour-water paste stripe approximately 1 mm wide painted down the center of the upper surface of the tongue and over the tongue tip, using as landmarks the sulcus medianus on the upper and lower surfaces of the tongue and the narrowing of the tongue to a point at its apex.

One low-light laboratory video camera was positioned at about 25° to each side of the subject's mid-saggital plane to capture a horizontal range of about 4 cm at the teeth or lower lip on one side of the mouth. The magnification afforded was 5:1.

Certain pieces of apparatus were used only in particular experimental conditions. Smooth softened chewing gum coated the back and lower edges of subjects' central eight upper teeth for the tests on tongue positioning inside the mouth in the absence of anesthetic. This covering precluded meaningful feedback about the accuracy of tongue positioning.

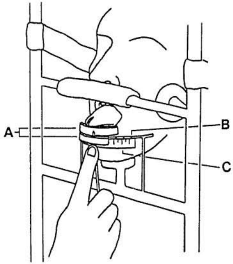

Figure 3.1 The headrest used in the horizontal position sense experiments (outside the mouth condition). A: The plastic curves attached to the pointer. B: The wire guide. C: The plastic scale. (Based on a photograph by Jack Martin)

For the conditions outside the mouth, a steel pointer was tapered to fit snugly into three notches 18.5 mm apart on a wire guide that stood 5 mm outside the subject's lower lip (see Figure **3.1**). The front side of the pointer was glued to the outside of a curve of plexiglass. A similar curve of plexiglass was glued to the back of the pointer directly below the first curve. The upper plexiglass curve sat directly on top of the wire guide, while the lower plexiglass curve lay against the wire, preventing movement of the pointer in the notch.

Certain materials were used to calibrate the apparatus. For the conditions inside the mouth a millimeter scale that copied the curve of the upper teeth was videotaped for 20 seconds in the position that the upper teeth would occupy during the experiment. For the conditions outside the mouth a scale on the headrest was videotaped (see C. Figure **3.1**).

3.1.3 Procedure

In all experimental conditions, the headrest was adjusted to fit the subject comfortably. The experimenter strapped the subject's head into the headrest. Subjects kept their eyes closed whenever they were in the headrest.

In each block of trials the experimenter indicated the three target positions in predetermined order to the subject. As each target was indicated, the subject aimed at it with the tongue. On completion, the subject left the headrest, and wiped the flour paste off the tongue. When the subject was ready, a new flour paste stripe was applied, the subject entered the headrest, and a new block of trials commenced. In total, there were six blocks of three trials in each condition. The subjects underwent the different conditions in different orders. No subject participated in more than one condition on the same day.

Certain procedures were followed in specific experimental conditions. In the experiment inside the mouth in the absence of anesthetic, the subject covered the back of his eight central upper teeth with softened chewing gum.

Then the experimenter painted a flour paste stripe down the center of the subject's tongue and over the tongue tip, and the subject then entered the headrest.

In each trial in the inside the mouth condition, subjects everted and retracted their upper lip, and the experimenter touched the subject's gingiva directly above one of three gaps between the upper six teeth with a paintbrush which had been dipped in the flour paste. The central target was defined as the gap between the subject's front incisors. The other two targets were defined as the gap between the second and third upper teeth on each side of the central target. The subject's task was to place the center of the tongue tip against the chewing gum that covered the bottom edges of the teeth directly beneath the place that the paintbrush had touched.

In the conditions outside the mouth, the following procedure was used. The central notch of the wire guide was placed in the mid-saggital plane of the subject's head, as nearly as the experimenter could judge. The experimenter painted a flour paste stripe down the center of the subject's tongue and over the tongue tip. Then the subject entered the headrest. The experimenter placed the pointer in the subject's hand, such that the index finger lay along the shaft. Then the experimenter guided the subject's hand so that it held the pointer upright against one of three notches in the wire guide. The notches used were the central one and the two that fell 18.5mm on each side of the central notch. The subject's task was to place the center of the tongue on the top of the plexiglass curve directly above the shaft of the hand-held pointer (see Figure **3.1**).

The anesthetic sessions were conducted in the same manner as the non-anesthetic conditions, with the following exceptions. Doses of 30 mg of Xylocaine were sprayed[1] as required on to the upper and lower surfaces of the anterior two thirds of the tongue before subjects entered the headrest. Testing showed that this was sufficient to ensure that they could not sense touch or pressure on the tongue.

The chewing gum was not applied for the condition inside the mouth in the presence of anesthetic, as the subjects could not detect the gaps between their teeth once the anesthetic had been administered.

3.1.4 Measurement

Subsequent to the experiments, measurements were taken from the videotape by stopping it when the tongue contacted the chewing gum

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[1] I am greatly indebted to Dr. Henry Manson, Anesthesiology, Faculty of Medicine, for his assistance with and advice on all anesthetic procedures followed in this thesis.

(i.e., in the condition inside the mouth in the absence of anesthetic), or the lower edge of the upper teeth (i.e., inside the mouth in the presence of anesthetic), or the top of the plexiglass curve on the pointer (i.e., outside the mouth). The image from a television screen was reflected in a horizontal half-silvered mirror such that it appeared to rest on the surface of a position transducer board (see Figure **3.2**).

The positions of the images of the target and the center of the (approximately 1 mm wide) stripe on the tongue were touched by a pointer. These positions were digitized and stored by computer. Calibration readings representing 2.5 mm of real space were also taken in this fashion from the scales. The error in my data due to imprecision of probe placement on the teledeltos board and to translating points on a curve to points in a plane was generally less than 0.5 mm (0.4° of lingual angle). To check for potential imprecision in measurement due to tongue tremor and to locating the center of the flour paste stripe on the tongue, inter-rater reliability checks were carried out on data from two subjects for two conditions, yielding $\underline{r} > 0.99$ in each data set (total $N = 48$). One of the two raters was naive as to the experimental hypotheses.

A small number of trials for most subjects and an entire session for one subject failed to provide measurable data because the tongue tip curled upward, obscuring the view of contact between the tongue and the lower edge of the upper teeth.

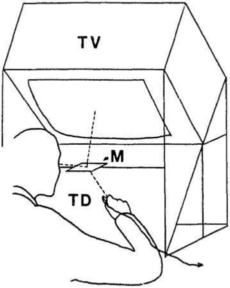

Figure 3.2 The measurement apparatus. TD: Teledeltos board. M: Front surface mirror. TV: Television monitor.

Since the errors in horizontal tongue position were measured at two distances from the root of the tongue, two different measures in mm represent identical angular errors. The correction factor to convert errors in mm to lingual angle for the data from the outside the mouth condition was 0.83. This is the ratio of tongue length at the teeth (based on the argument that the tongue can be treated as a pointer (tip to root) and is a standard length, 80 mm long (from cadavers collected by Kahane, 1982) and extensible to 96 mm long at the wire guide. Errors in positioning are presented both as errors of angle and as horizontal errors.

The data were normalized; I allocated the value of 0.0 to the average position (for each session) of the central gap between the front incisors. Each subject's non-anesthetic data were submitted separately to multiple regression analyses. The position of the tongue was regressed upon the target position. Also, the absolute difference between tongue and target position was regressed simultaneously upon vectors for proximity to tongue root (the inside/outside the mouth vector), lateral target position, the interaction between these two vectors, and the square of the target position. A t test tested the difference between the anesthetic and non-anesthetic data for the two subjects who had undergone the anesthetic treatments.

3.2 Results

The subjects were able to use their tongue to point at the horizontal targets accurately. For each subject, the proportion of the variance in the position of the tongue that can be attributed to the position of the target is statistically significant. Target location accounted for over 60% of the variance in tongue location for each subject, and for over 90% of the variance in the data of two naive subjects. These findings were statistically significant for every subject ($p < 0.001$). Subjects clearly know where the target positions are and can indicate them accurately with their tongue, demonstrating that they perceive tongue position.

I assume that the location of a punctate stimulus on gingival skin is perceived with little error, since there is no evidence in the literature that normal skin shows a drift in established position sense. As a result, the error in tongue placement inside the mouth can be viewed as being due in large part to the only moveable component, namely, the tongue. The mean absolute difference between target location on the gingiva and tongue position was 2.1° (2.9 mm) at the teeth for the unanesthetized tongue, and 2.0° (2.8 mm) in the anesthetic trials.

However, in the data from outside the mouth, errors in positioning have two sources, perceived tongue and perceived finger position; both tongue and fingertip have many degrees of freedom and both presumably rely on kinesthesis for positional information. Accordingly, in what follows, I have partitioned the error in aim at the handheld target equally between tongue and fingertip.

The absolute error in positioning the tongue outside the mouth then is 2.0° (2.8 mm) in the unanesthetized tongue, which is not significantly different from the size of errors inside the mouth for any naive subject and is similar to errors that previous research has associated with positioning the limbs (eg. Slinger & Horsley, 1906; Merton, 1961; Horch et al., 1975; Clark et al., 1985; Clark et al., 1986). A statistical test of the standardized Beta values associated with the inside/outside the mouth vector indicated that one non-naive subject positioned the tongue more accurately inside compared to outside the mouth ($\underline{B} = 0.33$, df per subject: 4,31, $p < 0.01$). These results suggest that position sense in the tongue is at least as accurate as kinesthesis in the limb.

Table 3.1 Mean error in horizontal position of the non-anesthetized tongue (degrees of lingual angle).

		Pointer Position					
		Left		Center		Right	
		Mean	SD	Mean	SD	Mean	SD
Mean Signed Error	Inside Mouth	1.7	2.9	0.2	1.1	0.3	1.8
	Outside Mouth	4.0	1.1	1.1	1.1	-1.6	1.0
Mean Absolute Error	Inside Mouth	2.4	2.1	0.9	0.8	2.9	1.9
	Outside Mouth	3.4	1.8	1.0	1.3	1.6	1.6

Note. Positive values for signed error represent errors to the right of the pointer. Pointer positions were approximately 18.5 mm apart. N = 4 subjects for the data from inside the mouth; N = 5 otherwise.

The administration of anesthetic to the mucosa did not affect the accuracy of the two subjects who were anesthetized. Their mean absolute errors in tongue positioning were uniform in the control and anesthetic data, being 2.0° (2.8 mm) at the teeth and 2.1° (3.6 mm) beyond the lip. The comparison did not produce a statistically significant difference for either subject. I conclude that structures that were not affected by the anesthetic can account for position sense in the tongue.

The absolute difference between tongue and pointer position was at its largest for trials on the left side outside the mouth, resulting in a statistically significant interaction for 3/4 subjects in the non-anesthetic condition (mean $\underline{B} = 0.30$, $\underline{df}$ per subject: 4,31, $\underline{p} < 0.02$).It can be seen from Table **3.1** that the perception of the tongue's position is highly accurate in the center of the mouth. The data in the Center column are generally close to 0, which represents perfect performance. These larger errors belong to a consistent trend toward increasing error in positioning, the further the target was from the center, and the further the target was outside the mouth. Indeed, the mean absolute error in tongue positioning tends strongly to increase with the square of the lateral distance from the center of the mouth (mean $\underline{B} = 0.59$, $\underline{df}$ per subject: 4,31, $\underline{p} < 0.01$ for 4/5 subjects, $\underline{p} < 0.10$ for 1 subject). The reason for the decrease in accuracy with greater deviation from the mid-saggital plane at the mouth is not known, but has been previously remarked with respect to the mid-saggital and mid-transverse planes for kinesthesis in the limb (Slinger & Horsley, 1906; Merton, 1961).

Due to procedural difficulties of target placement, the mean target position for the data gathered beyond the lower lip was 1.4° (2.0 mm) to the left of the central gap between the subjects' teeth, so the extreme target positions were not, on average, perfectly symmetrical about the central gap between the subjects' front incisors. In fact, the left target was 2.9° (4.0 mm) more eccentric than the right target. From the foregoing, therefore, it is not surprising that the errors in positioning were largest for attempts at the left target outside the mouth, given the exponential increase in error with greater eccentricity.

3.3 Discussion

A sense of tongue position exists. Subjects are able to perceive the position of their voluntarily moved tongue in horizontal planes both inside and outside the mouth with similar accuracy, about 2^0. This accuracy is in line with that reported by other authors for kinesthesis in the limb.

The argument for the muscular origin of the sensory information is strong, since subjects received no relevant tactile information about the target and anesthesia of the mucosa did not diminish the perception of tongue position, indicating that elements other than the skin of the tongue must be able to confer knowledge of tongue position. However, it is equally valid to posit a role for suitably calibrated motor instructions.

The hypotheses that were laid out in Chapters **1** and **2** have been supported. People perceive tongue tip position as accurately as they do the position of the limbs and the skin is not the only organ that conveys the relevant sensations to the brain.

CHAPTER 4

VERTICAL POSITION SENSE IN THE TONGUE

Chapter 3 demonstrated that subjects can sense the position of their tongue after active movement. I wished to investigate further the question of map calibration. Therefore I conducted an experiment in which subjects were given the opportunity of correcting or calibrating their map of lingual position. A comparison of performance before and after subjects were informed of their errors would furnish evidence about updating the map.

I speculated that the accuracy and extent of any sensory map might be improved by providing subjects with information about their success at moving to a goal in an unfamiliar region. In sum, the positioning of the tongue was expected to be at first somewhat inaccurate over the unfamiliar range and to become more accurate after information about the success of movements was given, thus allowing the sensory map to be calibrated.

A space somewhat unfamiliar to the tongue was required. Consequently, I used vertical targets outside the mouth, in the median saggital plane of the head. An experimental range of 30 mm in a vertical plane at 5 mm beyond the lower lip represented a space which could be expected to fall within the bounds of the sensory map of the tongue's range, since this range intersects with that used outside the mouth in Chapter **3**. As in the experiment in Chapter **3**, I used a kinesthetic target, an extension of the finger tip. Also, as in Chapter **3**, I reasoned that the errors in tongue positioning could be partitioned equally, supposing that the knowledge of fingertip position is as imprecise as that of tongue position.

The expectations:

1. Subjects should be able to point their tongue at kinesthetically defined targets, demonstrating that they could sense tongue position. Pointing of the tongue should be accurate to within a few degrees on average, as was the case outside the mouth in a horizontal plane (Chapter **3**).
2. The sense of tongue position in a relatively unfamiliar region might be initially crude, but should improve after the subjects are given information about their success at contacting kinesthetic targets.

It was important that the subject not receive any information about her success at this task in the first instance, and so a barrier was placed between the finger and tongue tip to preclude contact initially.

4.1 Method

I measured the pre- and post-treatment position of the untrained tongue in a vertical plane outside the mouth. The treatment comprised trials that informed subjects of their tongue height relative to their index finger height.

4.1.1 Subjects

One unpaid female aged 30, two male and seven female paid volunteers aged between 18 and 35 with no history of speech impairment or motor disorder participated in this experiment. Two of the paid subjects and the unpaid subject had also participated in the experiments described in Chapter **3**. No paid subject had any opportunity to practice the experimental task before participating in the experiment. The unpaid subject (CG) had carried out the experimental tasks approximately twenty times over several weeks before participating in the experiment.

4.1.2 Materials

A headrest incorporating a padded nose bar, a chin rest and a headstrap was used to keep the subject's head in position during all trials (see Figure **4.1**). A scale was suspended from the headrest so that it stood nearly vertical in a frontal plane 5 mm beyond the subject's lower lip, facing away from the subject. Attached to one side of the scale was a copper wire notched at 10 mm intervals. On the headrest, a shelf for the subject's wrist stood at the height of the center of the mouth. Two steel knitting needles with a collar at 17 mm (one needle) and 24 mm (other needle) from the point were used as pointed extensions of the finger tip.

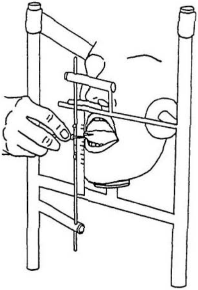

Figure 4.1 Headrest used in the vertical position sense experiment (based on a photograph by Jack Martin). The flour paste stripe is shown for ease of exposition as being on the side of the tongue contralateral to the pointing fingertip. In the experiments it was on the ipsilateral side.

A fiducial stripe of paste made with 4 parts flour to 3 parts water was painted down one side of the subject's tongue, terminating at the tip, midway between the top and bottom of the tongue. The experimenter used the same landmark when painting the stripe each time, namely the border between the smooth tissue on the inferior surface and the papillae on the superior surface of the tongue.

A video camera was mounted at approximately 25° to the mid-saggital plane in front of the subject and was set to capture more than the vertical 30 mm defined as the experimental range at 5 mm in front of the subject's mouth. This allowed a magnification of 5:1 and precision of reading the scale to better than 0.5 mm. Experimental sessions were recorded with a laboratory low-light camera and a video cassette recorder. A television was used for play back.

4.1.3 Procedure

The headrest was adjusted to fit subjects comfortably. Subjects moved their tongue outside the mouth as far upwards and downwards as they could comfortably go to define the center of the experimental range. The scale was centred in this range. Subjects kept their eyes shut and their head was strapped in place whenever they were in the head rest.

The experimenter painted a flour paste stripe along the edge of the subject's tongue ipsilateral to the preferred hand. The subject then entered the head rest. The experimenter placed the steel pointer with the collar at 17 mm in the subject's hand so that the subject's near-horizontal index finger pointed along the shaft toward the point. The subjects placed their wrist upon the shelf such that their hand rested next to their mouth. Then the experimenter guided their hand so that the pointer slid into one of the notches in the wire beside the plastic guide, with the collar minimizing the pointer's movement.

During each block of trials the subjects' task was to let the experimenter guide their hand so that the pointer lay in each of the four notches in a predetermined order, and, after each movement of the pointer to a new notch, to protrude their tongue so that the horizontal center of the tongue tip contacted the plastic strip at the height of the pointer extending from the finger tip. Between blocks of trials, subjects left the headrest, wiped the stripe from their tongue, and a new stripe was painted on. Each block comprised four trials and there were in total 4 blocks, making a total of sixteen trials per subject per session. The order of trials within each block was varied so that four different heights were attempted in each block, and no height was attempted in the same serial position twice.

In the first experimental session, subjects were kept in ignorance of their accuracy, so the metal pointer with a collar that prevented it from extending beyond the edge of the scale was used, thereby precluding contact with the tongue. The back and sides of the scale provided no tactile landmarks which would have given the subjects information. In a second session, the procedure described above was followed again, except that the pointer with the collar 24 mm from the tip was used. This pointer extended 5 mm beyond the edge of the plastic and subjects knew they were successful when their tongue contacted the pointer. In this second session, each trial ended only when the subject had contacted the pointer with her tongue. The third experimental session mimicked the first session exactly and immediately followed session 2. Sessions 2 and 3 took place at least 24 hours after session 1. All sessions were videotaped, but measurements were taken only for sessions 1 and 3.

4.1.4 Measurement

The heights of the center of the flour paste stripe on the tongue tip and of the pointer held in the subject's hand were read off a television monitor to the nearest half millimeter (0.3° of lingual angle) from the scale.

For two subjects' attempts at the extreme targets, a total of 11 values over four sessions had to be estimated, rather than measured, because the tongue contacted the scale too low or too high to allow the stripe to be fully visible. The tongue position greatly exceeded the range previously defined by the subject as being comfortable, and was well beyond the pointer.

A reliability check was used that required two analysts to estimate the height of the center of the flour paste stripe on the tongue in one of the sessions with estimated values. The correlation between the two analysts' measurements of 16 pairs of attempts by the tongue yielded $\underline{r}$ = 0.99.

Each subject's data were submitted to regression analyses. Tongue height was regressed on pointer height. Partitioned absolute error was regressed upon a vector representing pre- versus post-treatment, and partitioned signed error was regressed upon pointer height.

4.2 Results

The results show that the ability to perceive vertical tongue position is sufficiently accurate to allow subjects to direct the tongue tip successfully to a kinesthetically defined target. The nine naive subjects were able to point with accuracy at the four different target heights across both sessions (before and after being informed of their success at positioning the tongue), with the proportion of the variance in position of the tongue largely accounted for by the height of the pointer in the hand. This effect was statistically significant for each subject, with mean standardized $\underline{B} = 0.73$, $\underline{df}$ per subject: 1,30, $\underline{p} < 0.01$.

Information about the actual height of the hand-held pointer, provided in session 2, did not significantly improve the naive subjects' accuracy in session 3. In the pre-test session, the mean absolute error in tongue positioning for naive subjects was 2.5° (4.2 mm), while in the post-test session it was 1.9° (3.3 mm). This improvement of 0.6° (1.1 mm) did not reach the 0.01 level of statistical significance for any of the 8 subjects who showed the improvement: mean $\underline{B} = 0.17$, $\underline{df}$ per subject:

1,30, $p < 0.01$.

A comparison of the nine naive subjects' results with those of the practised subject revealed that the practised subject positioned her tongue more accurately overall than did any naive subject. Substantial practice (or motivation) appears to allow for more refined calibration than does the relatively short session wherein subjects received information about their accuracy.

A clear pattern of errors (mean signed error in tongue positioning) is evident in all subjects' data (see Table **4.1**).

Table 4.1 Mean signed error in vertical tongue position (degrees of lingual angle)

		Treatment			
		Pre-treatment		Post-treatment	
		Mean	SD	Mean	SD
Pointer Height	Top	-1.9	1.4	-2.1	1.1
	Upper Middle	-0.6	2.2	-0.6	1.6
	Lower Middle	1.0	2.1	0.8	1.5
	Bottom	2.3	1.7	2.2	1.4

Note. N = 9 (naive subjects only). Pointer heights were approximately 10 mm apart. A negative error represents the case where the tongue was lower than the pointer.

Within both experimental sessions the targets were undershot, permitting the reasonable assumption that the center of the experimental range served as a starting point for excursions of the tongue. This correlation between the direction of error and the height of the target is statistically significant for 7 of 9 naive subjects, mean $\underline{B} = 0.66$, $\underline{df}$ per subject: 1,30, $\underline{p} < 0.01$. Pointer placement was highly accurate and scarcely varied; the error lies in tongue placement.

4.3 Discussion

I expected that the naive subjects' sense of tongue position would be fairly accurate. The mean absolute error in tongue positioning of 2.1° (3.5 mm) across both experimental sessions for the naive subjects squares with that expectation.

The vertical and horizontal experiments involving fingertip and tongue as target and pointer, respectively, produced virtually identical errors in positioning the tongue, both revealing mean absolute differences between tongue and pointer position of about 2°, after partitioning the error between tongue and fingertip.

It is interesting that there was no significant improvement in 8 of 9 naive subjects' accuracy following the provision of information about fingertip and tongue positions provided in session 2. The initial positional calibration of the tongue by the naive subjects was fairly accurate.

CHAPTER 5

SENSING IMPOSED LINGUAL POSITION

It is important for an animal to know whether its body parts are being moved by an external agent, and where they are being placed. Otherwise, recovery of balance after stumbling over an unseen obstacle would be extremely difficult. Sensing a limb position imposed by an external agent is called sensing imposed position.

The earliest examinations of lingual position sense investigated imposed, rather than active, position sense in the tongue, for they sought to separate the contribution to sensing position of the muscular elements from that of knowledge of the outgoing commands to the muscles, or efference. Clearly, if an organ is moved by an external agent, and the subject does not resist or aid the movement, no commands to move can have been issued, and so any sense of position must be due to afference arising from imposed movement. It should be noted that procedures to verify that the subject has not abetted or hindered the imposed movement have not generally been applied in past experiments (eg. Goldscheider, 1889; Carleton, 1938; Adatia & Gehring, 1971); this remains a problem in modern work.

Early tests of kinesthesis in the externally manipulated tongue produced unclear results: only one of Carleton's (1938) eight subjects was able to nominate perfectly the direction of imposed tongue pull when the surface of the tongue was anesthetized. There are indications that her procedures may have been uncomfortable, a problem which is known to affect the clarity of kinesthetic sensation (Goldscheider, 1889), and that the large doses of anesthetic she used infiltrated the proprioceptive elements in the muscles (Adatia & Gehring, 1971).

Carleton's work stands alone as an experimental study that suggested that the ability to sense imposed tongue movement might not exist. Adatia and Gehring (1971) on the other hand found that eleven of their twelve subjects had no difficulty determining the direction in which their externally manipulated tongue had moved after the lingual nerve had been blocked with lignocaine and adrenaline.

I wished to test for the presence of kinesthetic sensation when the tongue was moved by an external agent. I used vertical and horizontal targets in the median saggital and transverse planes of the mouth, as in Chapters 3 and 4.

I wished to use an experimental range comfortably accessible to the tongue. My experimental range of 20 mm in vertical and horizontal planes at 5 mm beyond the lower lip represented a space which could be expected, based on Chapter 3's and 4's results, to fall within the bounds of the sensory map of the tongue's range. I expected evidence of ability to sense an imposed tongue position to be forthcoming over this range.

My hypothesis:

> A subject should be able to sense the direction in which the tongue is being moved by an external agent, both in the presence and absence of tactile information from the surface of the tongue.

This would reveal the existence, and to some extent, imply the nature, of kinesthesis when voluntary control of the tongue is at a minimum.

5.1 Method

The experiment served as a refined replication of Carleton's 1938 experiment. She tested whether subjects could correctly nominate the direction in which their tongue was being moved by an experimenter after its surface had been anesthetized with cocaine. I used Xylocaine and sought to avoid the influence of deep pressure sensations on kinesthesis and the distracting effect of introducing large objects such as pliers into the mouth. To this end I used an unobtrusive lightweight plastic cap sucked onto the tongue tip; by means of thread this could easily be manipulated at some distance by the experimenter. I conducted the experiment under four conditions: with and without anesthetic, and with horizontal and vertical tongue movement.

5.1.1 Subject

One adult female with no known history of speech or motor problems was used in both conditions. The subject (CG) had no practice at the task prior to the experiment.

5.1.2 Materials

A piece of light nylon thread 150 mm long was threaded through the tip of a plastic pen cap 17 mm long and glued inside the tip. The anesthetic used was a 4% solution of Xylocaine.

5.1.3 Procedure

The sessions were conducted in the following order: horizontal control, horizontal anesthetic, vertical anesthetic, vertical control. The anesthetic conditions were imposed on the same day. At least 24 hours elapsed between the control and anesthetic conditions.

A total of 50 mg of the 4% solution of Xylocaine was sprayed on the upper and lower surfaces of the tongue[1]. Once the subject could no longer sense contact between the tongue and an object placed in the mouth the experimental task commenced.

The subject sucked the plastic cap securely onto her tongue tip and

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[1] I am greatly indebted to Dr. Henry Manson, Anesthesiology, Faculty of Medicine, for his assistance with and advice on all anesthetic procedures followed in this thesis.

held her mouth open, producing an aperture of about 30 mm between upper and lower teeth, such that the tongue and cap did not contact the mouth or teeth. The subject kept her eyes shut throughout. The experimenter was careful to avoid contacting any part of the mouth with either the cap or the tongue. The experimenter then moved the tongue tip by pulling the string attached to the cap upwards or downwards, to the left or to the right of the subject.

Three different tongue tip positions were used for each movement condition. For the vertical conditions these were the positions: approximately 10 mm above horizontal, horizontal, and 10 mm below horizontal. At horizontal, the tongue tip protruded midway between upper and lower teeth. For the horizontal conditions the three positions were: approximately 10 mm left of center, center, and 10 mm right of center. At center, the tongue tip occupied the mid-saggital plane. The order of the positions varied randomly. There were seven trials at each position for a total of twenty-one trials per condition. The trials took three minutes for each condition in total.

The subject's task was to communicate the perceived location of the tongue tip at the end of each trial. She did this by gesturing with her index finger in the appropriate direction: upwards, horizontal or downwards, left, center, or right. The procedure for the control condition was exactly the same as that described above, except that no anesthetic was administered to the subject.

5.2 Results and Discussion

The subject made no errors in nominating the position of the tongue tip in either anesthetic condition and found the task very easy. She made two errors in the vertical control condition and none in the horizontal control condition.

While the subject indicated by upward movements of her index finger that she sensed the upward movement on the two erroneous trials, she failed to show that the high tongue position was ultimately adopted. The subject's nearly perfect performance indicates a well-developed ability to sense the position of the tongue, even when not the main agent of its movement.

It is of course possible that the subject might have involuntarily abetted or resisted the imposed movement to a minimal extent, in which case a small amount of involuntary efference might have arisen. I have assumed that this unknown source of efference has contributed negligibly to the results, if at all, as have previous workers in the area (eg. Craske & Crawshaw, 1975a) and so conclude that the subject probably has access to, and interprets, sensory afference that arises from the imposition of tongue movement. The problem of unintentional muscular contraction during imposed movement tasks has been recognized elsewhere (Goodwin et al., 1972; Craske & Crawshaw, 1975a).

This result is similar to Carleton's results from one of her eight subjects and to Adatia's and Gehring's results from eleven of their twelve subjects. It suggests that subjects can sense the position of their tongue well when the method of tongue manipulation is quite unobtrusive. Carleton's technique of pulling the tongue about with a pair of pliers may have elicited sensations of deep pressure which obliterated, masked, or took precedence over, any sensations of tongue position. This would explain the great variation in her results and at the same time account for the ease of the task for the subject here.

These data support arguments in favor of muscle and tendon afference providing kinesthetic information about tongue position. Muscular afference is a likely candidate for signalling the tongue's position, for nomination of position was perfect after the mucosa were anesthetized, eliminating tactile sensation. There was presumably little or no corollary discharge, since the movement was imposed.

On some trials it was observed that the subject must have monitored her tongue movement and/or position continuously, for she did not always wait until the end of the trial to indicate that its final position would have to be above or below horizontal, or to the left or right of center. This ability to monitor change in position and direction of tongue movement suggests that at least the sense of direction of movement is likely to be accurate even over small distances, for the vertical range of movement here was in total approximately 20 mm.

It is not valid to consider this range as necessarily revealing the accuracy of the sense of tongue position itself, rather than a sense of movement. Thus, the subject might have needed only an accurate sense of direction of movement and the ability to sense the straight ahead to produce the above results. Nonetheless, these too are sensations that deserve the label kinesthetic (see Howard & Templeton, 1966), and could furnish a basis for deducing lingual position.

A more precise matching procedure could provide clearer evidence of the precision of sensing imposed tongue position, as implied in reference to a test of sensing the direction of finger movement that is similar in some respects to the experiment here (eg. Ferrell et al., in press). For example, if more numerous tongue positions were used as test positions, subjects would have to judge, and indicate position more precisely.

CHAPTER 6

THE AFTER-EFFECT OF LOADING THE TONGUE[1]

This chapter describes an experimental investigation into the existence of lingual position sense and the nature of the underlying sense organs. To the extent that the tongue uses kinesthetic mechanisms that are based on muscle, I would expect to find normally good position sense in the tongue, which can be biased by loading the tongue causing it to strain against a force, as Chapter **2** explained. By <u>strain</u> I mean the effortful maintenance of a limb or tongue position against a force. In what follows, the strain by the tongue is in the direction opposite to that of an externally applied force.

By examining the effects of loading on position sense in the normal and surface-anesthetized tongue, I should have evidence concerning the role of the cutaneous sheet as a sensory source of lingual kinesthesis. Given the articulatory imprecision evident during topical lingual anesthesia (eg. Scott & Ringel, 1971), I asked whether normal tactile sensation would reduce any after-effect by overwhelming the sensations based on muscular afference that might contribute to it. An experiment

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[1] The contents of this chapter have appeared in published form as a paper entitled: The effect of loading on position sense in the tongue (Grover & Craske, 1991).

was designed to answer these questions, which are formulated as hypotheses:

1. Straining the tongue against a horizontally acting force should produce errors in judging the straight ahead with the tongue. Subjects should tend to place their tongue in the direction of previous effort or strain, thus indicating that they perceive the tongue to occupy a position farther in the direction opposite to that of the previous effort than is objectively the case.
2. The skin of the tongue may contribute important information about tongue position, in which case errors in tongue positioning should be smaller when the lingual mucosa are not anesthetized.

The pattern of decay of the after-effect should also be examined. There is, to my knowledge, no detailed information in the literature on the trend of the decay of the after-effect of loading a limb. As this information might prove to be interesting, it will be sought.

6.1 Method

An after-effect of muscular strain was solicited by loading the tongue with a 29.5 g weight for 30 seconds.

6.1.1 Subjects

Five female and five male adults aged 18 to 50 participated. The eight naive paid subjects completed all non-anesthetic conditions, one unpaid subject performed in all four conditions (CG), and the other unpaid subject took part in three experimental conditions. The naive subjects were not aware of the experimental hypotheses.

6.1.2 Materials

A headrest incorporating a padded nose support, chin rest and head strap was used to keep the subject's head in position during the experiment (see Figure **6.1**).

The headrest supported a flat plastic sheet 75 mm wide and 39 mm deep in a horizontal plane. This scale nearly abutted the subject's lower lip. It was marked in degrees of arc for later use in measuring tongue position from videotape. A range of 20^0 of lingual angle, centered about the mid-saggital plane, was represented. Following Kahane (1982), lingual angle was calculated assuming a tongue length from root to the lower teeth of 80 mm.

A brass mass of 29.5 g was attached with a piece of lightweight nylon thread to a truncated plastic cap 17 mm long through a small hole drilled in its side 3 mm from the base. This mass hung freely when suspended over a small pulley on the headrest.

A 20 mm square front surface mirror was attached to a wedge of

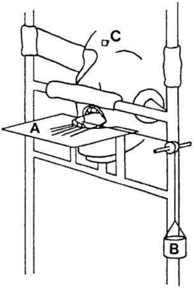

Figure 6.1 The headrest for the loading experiment. A: Scale marked in degrees. B: Mass suspended over a pulley. C: Mirror on forehead. (Based on a photograph by Jack Martin)

adhesive-backed sponge. This was fixed to the center of the subject's forehead, and remained there throughout the experiment. It reflected an arrow of light onto a section of wall marked in degrees of arc relative to the head. The experimenter maintained the subject's head in position by ensuring that the reflected light remained within a pair of demarcations on the wall denoting 0.5^0 of head rotation in a horizontal plane.

The fiducial mark on the tongue was a semi-permanent dark dot made with a non-toxic felt pen and a flour paste (4 parts flour to 3 parts water) dot overpainted on this with a size 00 paintbrush. This coincident pair of dots was in the center of the upper surface of the tongue tip and served as the visible mark for the video camera.

A low-light video camera was positioned in the subject's mid-saggital plane so that tongue movement against the background of the plastic scale could be videotaped with a magnification of 5:1. The position of the tongue in half degrees of lingual angle was easily read off from the magnified image.

6.1.3 Procedure

The logic of the experiment was as follows. Judgments of tongue position before and after loading were to be compared. Accordingly, three blocks of control trials (before loading) and one block of experimental trials (after loading) were conducted.

There were three blocks of control trials, rather than one, in order to ensure that effects associated with the experimental trials were indeed due to the horizontal load and not merely to the exertion of effort required simply to protrude the tongue straight ahead. Thus, in the first and third basic control blocks of trials, the subject judged the straight ahead by positioning the tongue. In the second protrusion control block of trials the subject protruded the tongue for 30 seconds before judging the straight ahead with the tongue.

The order of blocks of trials follows:

1. Control trials
    a. Judgment of the straight ahead with the tongue.
    b. Protrusion of the tongue straight ahead for 30 seconds, followed by judgment of the straight ahead.
    c. Judgment of the straight ahead with the tongue.
2. Experimental trials
    a. Protrusion of the tongue straight ahead, the position being maintained against a horizontally applied load for 30 seconds, followed by judgment of the straight ahead after the load had been removed.

Each experimental condition comprised 4 blocks of 10 trials in the above order. The order of blocks did not vary. Subjects participated in the experiment one at a time, and rested between each block of trials.

Once the headrest and the accompanying apparatus had been adjusted so that the subject was comfortable, the subject left the headrest and videotaping commenced. The experimenter made a dark dot with the felt marker in the center of the upper surface of the subject's tongue tip. This dot did not fade during the course of the experiment. Before each block of trials the experimenter placed a dot of flour paste on top of it.

The subject entered the headrest and the experimenter fastened the headstrap around the subject's head. Subjects shut their eyes at this point and kept them shut throughout all trials. Subjects opened their mouth so that the lower jaw was stationed on the chin rest and the nose on the nose bar. They maintained this position throughout each block of trials. The experimenter placed her hands on the subject's head to keep it in position. Then she instructed the subject to judge when the tongue felt to be straight ahead, using the method of adjustment. When the experimenter called out "left", for example, the subjects protruded their tongue from the left side of the mouth, moved the tongue to the right until they were satisfied that it was straight ahead, and then dropped it gently onto the plastic scale, and knocked on the table to indicate that the tongue was straight ahead and on the scale. Then they retracted the tongue and the next trial began.

Trials starting from the two sides of the mouth alternated, for a total of 10 trials per block. Trials each took about 3 seconds, on average. After completing a block of trials, subjects exited the headrest, wiped the flour paste off the tongue and rested.

Blocks 1 and 3 proceded in this fashion. In block 2 (protrusion control), the subjects protruded their tongue straight ahead for 30 seconds, taking care not to touch it to the plastic scale. The experimenter then painted a flour paste dot on top of the dark dot on the subject's tongue and subjects judged the straight ahead 10 times, as before. The subject then left the headrest and wiped the flour paste off the tongue.

Before block 4 (the experimental block), the subject sucked the plastic cap onto the tongue tip and entered the headrest. Then the subject protruded his tongue and the mass was gently released over the pulley. The subject's task was to maintain the tongue straight ahead for 30 seconds without letting it rest on the plastic scale. Once the 30 seconds had elapsed, the experimenter released the suction, removed the cap from the subject's tongue, and painted on a flour dot. Subjects judged the straight ahead 10 times.

All conditions were composed of sets of these four trials. The various conditions were: performance with anesthesia of the mucosa, performance without anesthesia of the mucosa, performance following loading on the right side of the subject - due to a weight pulling the tongue to the right, and eliciting strain to the left, and performance following loading on the left side of the subject - due to a weight pulling the tongue to the left, and eliciting strain to the right. The subjects underwent the various conditions in different orders, with at least a day between participation in any two conditions.

Two subjects took part in the anesthetic conditions in an earlier version of this experiment. These conditions were similar to the non-anesthetic conditions described above. Procedural differences were as follows. Anesthesia of the mucosa[2] was induced before any trials were conducted. The mirror on the forehead and the dark dot on the tongue were not used. In their place, head position was monitored by recording the position of a flour paste stripe on the lower lip directly before every block of trials. Also, the flour paste dot was repainted in the same place on the tongue each time using landmarks, including the central sulcus. Lastly, trials occurred at timed 3 second intervals and subjects did not need to knock to indicate when they felt the tongue to be straight ahead.

A dosage of 60 mg for one subject, and 90 mg for the other, of a 4% solution of Xylocaine was administered to the upper and lower surfaces of subjects' tongues. Testing ensured that this was sufficient to eliminate sensations of contact and pressure between the tongue and objects placed in the mouth.

6.1.4 Measurement and Analysis

The videotaped sessions were played back on television. Measurement of the straight ahead of the subject's head in the anesthetic condition was taken by stopping the videotape when contact between the lower lip and the plastic scale was seen to occur, and reading off from the image of the scale the location of the center of the stripe on the lower

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[2] I am greatly indebted to Dr. Henry Manson, Anesthesiology, Faculty of Medicine, for his assistance with and advice on all anesthetic procedures followed in this thesis.

lip to a half degree of arc.

For the anesthetic condition judgments with the tongue of the straight ahead were measured by stopping the videotape when the tongue tip was seen to protrude to its furthest point and reading off to a half degree of arc the location of the center of the dot on the tongue tip with respect to the markings on the scale. Changes from an arbitrary zero indicated by the lower lip marker were subtracted from the measure of tongue position for each trial of a block.

For the non-anesthetic condition, head position was kept constant, so the position of the flour paste dot was read directly from the scale off the videotape when the subject's knock was heard. In cases where the flour paste had been inadvertently smeared, it was often possible to discern the position of the dark dot and so that was used for measurement instead.

In total, there were 828 measurements of the tongue's position to analyse. One subject's data had to be discarded due to her failure to follow instructions. Another subject was not available for one session with the anesthetist for reasons unrelated to the experiment.

The occasional trial could not be measured due to failure of the tongue to contact the plastic scale or due to smearing of the flour paste. The other trial in the left-right pair was then also removed from analysis. For 6 data sets there are then 38 instead of 40 trials per subject.

A reliability check on data measurement was conducted on one subject's data from one session, using an analyst naive as to the purpose of the experiment. The correlation between the two analysts' measurements was $r = 0.93$.

Within each subject's non-protrusion control data in the non-anesthetic condition, the mean judged straight ahead was set to 0, and the standard deviation then calculated across all subjects' normalized data to yield a measure of the precision of the judgment of the straight ahead.

The statistical treatment was repeated measures multiple regression. The analysis required several steps due to the complex control trials. It was desirable to adopt one procedure for analysing all the data, and so all subjects' data were considered together, instead of being separated, as elsewhere in the thesis. Thus, the deviation of the tongue from the 0° (arbitrary) straight ahead was regressed upon the type of control trial (basic or protrusion), then upon the experimental versus combined control trials, considering each direction of strain separately. The variance due to the subjects vectors was removed from the regression equations before any effects were examined. The anesthetic data were compared to the non-anesthetic data for two subjects by means of t tests.

6.2 Results

First, I considered only the control trial data. Judgment of the straight ahead during the basic control trials did not differ significantly from judgments after protruding the tongue straight ahead for 30 seconds: for the non-anesthetic data, $\underline{B}$ (standardized Beta) $= 0.05$, $\underline{F}\ (1,520) = 2.24$, $\underline{p} = 0.13$, and for the anesthetic data, $\underline{B} = 0.12$, $\underline{F}\ (1,87) = 3.33$,

Table 6.1. Mean deviation of the tongue from 0° and SD in the non-normalized data (degrees of lingual angle)

		Direction of Tongue Strain			
		Left		Right	
Conditions		Mean	SD	Mean	SD
Non-Anesthetic Data	Control 1	-0.1	2.3	-0.8	2.2
	Protrusion	-0.6	2.9	-0.9	2.9
	Control 3	-0.5	3.3	-0.3	3.1
	After Strain	-1.2	3.2	0.4	3.0
Anesthetic Data	Control 1	0.7	1.3	0.2	0.4
	Protrusion	0.4	1.4	0.4	0.4
	Control 3	0.8	2.0	0.9	0.5
	After Strain	-0.5	1.0	1.7	0.6

Note. *Left*: Strain leftwards by the tongue arises against an external force pulling the subject's tongue to the *right*. The three control blocks preceded strain. A positive value indicates that the tongue was to the right of 0° on the plastic scale.

$\underline{p} = 0.07$. The mean deviation from 0° on the plastic scale (arbitrary straight ahead) and standard deviation were calculated. These statistics are presented in Table **6.1**. The data from the three blocks of control trials are reasonably uniform. Consequently, I collapsed the protrusion and basic control data so as to compare judgment of the straight ahead after loading the tongue to judgment of the straight ahead in all the control trials.

Table 6.2 Mean deviation from 0°: Data from Subject 6 (non-anesthetic condition: straining rightwards with the tongue)

Trial Type	Mean Lingual Angle	SD
Control 1	-0.6	0.6
Protrusion	-0.5	0.6
Control 3	-1.4	0.7
After Right Strain	0.8	0.3

I assumed that in the control trials the subjects would select a tongue position as being straight ahead and continue to select that position, relative to the scale. The scale was placed with the 0° mark approximately straight ahead of the subject (within 5^0 about the mid-saggital plane of the subject's head). Although the scale's zero is, strictly speaking, arbitrary, the consistent judgment of straight ahead as being centred at -0.55^0 (left of center) with a standard deviation across all normalized data of 1.6^0 within that central 5^0 implies that subjects know where straight ahead of the tongue is. A sense of the tongue's position exists and is reliable and accurate.

Horizontal strain by the tongue altered the sensed horizontal position of the tongue tip. After straining against the weight with the tongue for 30 seconds, during the judgment of straight ahead the tongue was placed further in the direction of the previous strain, as predicted. One subject's data is shown by way of example in Table **6.2**. Most subjects perceived the tongue to occupy a position further in the direction opposite to that of the previous effort than was objectively the case. For example, the tongue was placed further to the left after straining to the left, implying that the tongue was perceived as being further to the right after the strain than it actually was. This trend is clear from Table **6.1**; for the non-anesthetic condition after straining to the right: $\underline{B} = 0.16$, $\underline{F}$ $(1,342) = 19.1$, $\underline{p} < 0.001$ (after removing variance due to the subjects), and after straining to the left: $\underline{B} = -0.13$, $\underline{F}$ $(1,346) = 16.7$, $\underline{p} < 0.001$. For the anesthetic data the same effect holds (see Table **6.1**): after straining to the right, $\underline{B} = 0.72$, $\underline{F}$ $(1,38) \approx 40.6$, $\underline{p} < 0.001$, and after straining to the left: $\underline{B} = -.32$, $\underline{F}$ $(1,77) = 33.4$, $\underline{p} < 0.001$. This finding supports the hypothesis that muscular effort biases the sensed position of the tongue, such that the tongue is perceived to be further in the direction opposite to that of the effort than is true. This result conforms to previous data for other kinesthetic systems.

I inspected the decay of the effect of straining with the tongue. There was no statistically significant linear trend within the non-anesthetic data gathered after loading the tongue for either direction of strain: after

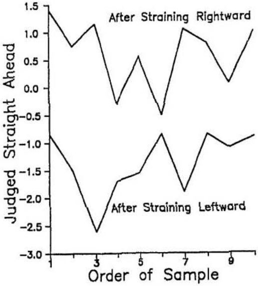

Figure 6.2 The decay of the effect of loading on judgment of the straight ahead for all subjects in the non-anesthetic condition. The 10 judgments per subject were made over approximately 30 sec after the load had been removed from the tongue.

straining to the right, F (1,78) = 0.63, $p > 0.05$, and after straining to the left, F (1, 80) = 1.45, $p > 0.05$ (see Figure 6.2). The weakness of the trends is due to the large variance in the data. Nonetheless, the trends in the two directions of strain were significantly different: F (1,168) = 10.1, $p < 0.01$ (regression of the interaction of order of sample and direction of strain, after removal of variance due to subjects).

To judge by the results above for the non-anesthetic data, the skin does not maintain the accuracy of position sense after the tongue has strained. Consequently, I expected that anesthesia of the mucosa would have little effect upon kinesthesis in the tongue, as strain against the weight should involve the muscles, and not the skin of the tongue. My results are inconclusive with respect to this question. A comparison of the effect of strain in one direction with and without anesthetic for the two subjects whose tongues were anesthetized produced conflicting results. No reliable trend was apparent.

Overall, the after-effect of the strain is similar to that observed elsewhere: from the previously judged straight ahead, a mean deviation of about 1^0 in the direction of previous strain.

6.3 Discussion

The tongue displays accurate position sense. The placement of the tongue in the pre-strain control trials was straight ahead of the subject. Subjects consistently judged to be straight ahead a tongue position 0.6° to the left of the line set by the experimenter as being approximately in the mid-saggital plane of the subject's head.

An after-effect due to effortful strain against a weight was elicited, as predicted. There are two possible interpretations of the after-effect, which are not mutually exclusive. The first explanation is that, after straining, the subject retains her knowledge of where straight ahead is, for example with respect to body parts other than the tongue, but misperceives the position of the tongue, perceiving it to be further in the direction opposite to the previous strain than is objectively the case. Consequently, to place the tongue such that its perceived position aligns with the straight ahead, she must place it further in the direction of the strain than she did in the control trials.

The second possibility is that, after strain, the subject considers straight ahead to be at a different lingual angle to the head, compared to that during the control trials, namely, further in the direction of strain, away from the mid-saggital plane. At the same time as the perceived straight ahead is shifted in the direction of the previous strain, tongue position is veridically perceived, and so the tongue is placed in the direction of the previous strain. It is also possible that both the straight ahead and tongue position are misperceived.

The first explanation is preferable, given the results from matching tasks during and after load. In experiments where the subject's task is to place one arm at the same angle as the other loaded arm (eg. McCloskey, 1973), there is no reason to propose that the position of the unloaded arm is misperceived, and good reason to expect the position of the loaded arm to be misjudged (see Chapter 2). Namely, the muscular discharge from the loaded arm can be presumed to differ from the unloaded (normal) circumstance. With respect to the experiments here, it is most economical to consider the perceived position of the loaded tongue to have been biased, resulting in erroneous positioning at a true straight ahead. Under this interpretation, I would not expect the straight ahead to be misjudged by other organs than the tongue following strain by the tongue.

The first explanation is consistent with the idea that muscular afference contributes to lingual position sense. The strain presumably influenced the afference from the muscle of the straining tongue, and/or biased its interpretation. However, it remains possible to claim that the perceived straight ahead has shifted, as in explanation 2 above. To be precise, this claim should be made <u>only</u> in reference to judgments by the loaded tongue, and therefore with respect <u>only</u> to lingual position sense.

The bias is not reliably affected by anesthesia of the mucosa. Therefore, the skin is not such a prominent source of positional information that it overrides the sense of the straight ahead furnished by muscle and tendon afference and the corollary discharge when the tongue bears a load.

CHAPTER 7

DISCUSSION OF LINGUAL POSITION SENSE

7.1 General Hypothesis 1: Existence of Lingual Position Sense

My results show that subjects are able to sense the position of the tongue. Clearly, subjects are able to sense the position of their voluntarily moved tongue on the left-right dimension in horizontal planes both inside and outside the mouth (Chapter **3**), and on the vertical dimension outside the mouth (Chapter **4**). Feedback about tongue position did not significantly improve the accuracy of positioning the tongue in the short term (Chapter **4**). The placement of the tongue in the pre-strain trials of the loading experiment (Chapter **6**) was a good approximation to straight ahead.

The tasks described in Chapters **3** and **4** fall into the class of position matching tasks that Ferrell & Craske (in press) have claimed should tap position sense as opposed to movement sense. However, the subject may have completed the horizontal and vertical pointing tasks described in Chapter **5** (a replication of Carleton's experiment) by consulting a sense of direction of movement in addition to knowing where straight ahead was. Nonetheless, it is clear that the subject could sense the position of her tongue following the imposition of movement by an external agent. Generally, although subjects were asked to judge tongue position, they may have relied on information about movement as well as, or even instead of, positional information.

7.2 General Hypothesis 2: Accuracy of Lingual Position Sense

The accuracy of lingual position sense is similar to that for the limb and eye. In comparison with other kinesthetic systems, I note that position sense in the limb is normally accurate to within 2° of joint angle if errors are partitioned equally between the two limbs whose positions are being matched (Goldscheider, 1889; Slinger & Horsley, 1906; Merton, 1961; Horch, Clark & Burgess, 1975; Clark et al., 1986).

Lingual position sense is equally accurate inside and outside the mouth, if the error in pointing the tongue at the hand is considered to be due to sensing target (fingertip) as well as pointer (tongue) position. My data from inside and outside the mouth show similar error for the tongue, about 2° (Chapters **3** and **4**). It appears that the regions both inside and outside the mouth are mapped accurately, even though much of the tongue's activity occurs inside the mouth. Thus, it is possible that limited activity in a region suffices to calibrate its map, or that accurate extrapolation of the sensory map into less frequently visited regions is possible.

My mean absolute error of 2.1° (2.9 mm, Chapter 3) inside the mouth seems larger than would be expected from Siegel's & Hanlon's (1983) work. However, their experimental range was only 20 mm, centered at the mid-saggital plane, whereas mine was 36 mm. I suppose that my errors would have been smaller over their range, given that the size of error increases with target eccentricity. Indeed, my value for mean absolute difference between central target and tongue position inside the mouth is 1.3 mm, which may not be significantly different from the Siegel & Hanlon error of about 1 mm.

The superior accuracy evident in the central region inside and outside the mouth and the undershooting of eccentric targets may have several causes. Given the greater accuracy in the center region, the problem is arguably one of calibration, which harmonizes with Slinger's & Horsley's (1906) proposal that ease of movement and frequency of prior experience might underlie the better accuracy of limb position sense close to the mid-saggital and mid-transverse planes. I speculate further that precise control of tongue position is required particularly in the mid-saggital plane inside the mouth for the articulation of numerous speech sounds in most languages, and so the sense of the tongue's position is calibrated most accurately for this region.

7.3 General Hypothesis 3: Sources of Lingual Position Sense

Muscular strain biases the sense of the tongue's position, strongly implying a role for muscular afference in lingual position sense (see Chapter **6**). The direction of pointing the tongue that is perceived to be straight ahead is shifted in the direction of the previous strain.

In the tongue pointing tasks (Chapters **3**, **5**, and **6**), position sense is good even in the absence of tactile information from the surface of the tongue, suggesting that muscle and tendon afference and efference contribute to lingual position sense. Anesthesia of the mucosa did not significantly reduce the ability to point accurately with the tongue, nor, for one subject, to indicate imposed tongue position.

In the investigation of the after-effect of straining with the tongue, information from the unanesthetized mucosa of the tongue should have provided veridical information, based on sensed deformation of the tongue surface, that might have reduced the bias (following strain) in judging the straight ahead, compared to the anesthetic condition. In fact, biases in judging the straight ahead with the tongue in the presence and absence of anesthesia of the tongue surface were of similar magnitude and identical direction. In the presence of misleading muscular afference and an unwilled motor discharge, the tactile afference from the deformation of the unanesthetized surface of the tongue fails to correct for the bias. This afference either fails to provide clues about tongue position, or is not attended to in this non-speech task. Elements other than the skin deserve a prominent place in discussions of lingual position sense.

My results are congruent with results from recent work on after-contraction in humans (Gregory et al., 1988; Hutton et al., 1984). The bias that I observed could be viewed as part of the after-contraction effect. Gregory et al. (1988) observed human subjects matching the position of one arm, whose biceps (or triceps) they had previously contracted, to that of the other untreated arm. The following bias arises: after contraction in a flexed position the arm is perceived to occupy a position that is further into extension than is the case after contraction in an extended position. This suggests that, after contraction, the spindles continue to supply afference.

Hutton et al. (1984) found that after large voluntary muscular contractions, humans underestimate for at least 50 seconds following contraction the force that they are producing with the previously contracted muscle (or overestimate the force of the previous contraction, which they attempt to match). If that afference is interpreted wrongly to provide an inaccurate reading of current position, my results for the tongue would be predicted.

While efference, in form of the corollary discharge, might also have informed the brain of the position in which the tongue tip was being placed during the positioning tasks, it is likely that the motor system cannot send the tongue to a place without first determining current tongue location. Accurate information about tongue position must be accessible to the subject.

I think that it is very likely that the corollary discharge is also a prime contributor to the observed bias. The following argument is speculative, due to the fact that it may be improper to consider the tongue to operate as a set of flexors and extensors. In the loading and protrusion conditions in my experiments, the entire tongue stiffened, and so one cannot speak of stretching and contracting muscle antagonists in the same fashion as for the limbs. The following argument argues in terms of two sides of the tongue, one which strained and one which did not. It may be valid for the intrinsic muscles which I suppose to have strained against the load.

I assume that the main protruder of the tongue in my experiments was the genioglossus, and that principally the intrinsic muscles pulled against the load (see Lowe, 1981). In agreement with Hutton et al. (1984) and Gregory et al. (1988), I assume that there is a motor after-discharge of unknown duration in the intrinsic muscles on the side of the tongue that principally strained against the load previously. This would result in movement of the tongue in the direction of the previous strain, movement of which the subject would be possibly unaware.

If I assume further that this after-contraction discharge continues as subjects move their tongue from the side of the mouth to the straight ahead, then the corollary discharge associated with this willed movement will continue to underrepresent the extent of actual movement in the direction opposite to that of the previous effort. Thus the corollary discharge should play a role in sensing position.

7.4 Concluding Remarks

It is of interest to discover that the tongue's basic principles of kinesthetic operation seem to be similar to those of jointed structures. The muscles, tendons, skin and corollary discharge probably provide rich information about tongue position. Knowledge of tongue tip position implies knowledge of tongue shape, subsuming length or width and tongue curvature. Knowledge of muscle length alone, for example, of the genioglossus or the intrinsic muscles' length (probably the important muscles in my experiments, see Lowe, (1981)), would be ambiguous in the tongue: theoretically, a particular muscle length could mean that the tongue is aiming to the right, or is curled, or is long and pointing straight ahead. Presumably, a knowledge of many muscles' length and of commands to the muscles would supply these pieces of information. I would also allow that in the normal case, afference from the skin about skin stretch is informative. It is not, however, likely to be crucial.

I did not explicitly test subjects' knowledge of tongue length, shape, or curvature, but argue that these must be known quantities prerequisite to knowledge of tongue position. Normally experiments on limb position sense do not explicitly consider knowledge of limb length; it is, however, always a necessary component for the analysis of position (see Craske, Kenny & Keith, 1984). Given my results on the tongue, I would be surprised if limb muscle and the corollary discharge could not, in appropriate circumstances, also supply information about limb length. It is already clear that the sensory map of the skin allows the recording and updating of such knowledge (Craske et al., 1984).

The similarity of position sense in tongue and limb is confirmed by the pattern of positional errors that my experiments revealed. The undershoot errors in aim are similar to those found in work on limb positioning (eg. Slinger & Horsley, 1906; Ferrell & Craske, in press) and eye positioning (Craske et al., 1975) in that the position of more eccentric targets tended to be underestimated.

Also, the direction and size of the bias that I elicited by loading the tongue concur with those mentioned in previous research on other organs. My mean shift in positioning the tongue after straining against a weight is about 1^0, whereas Craske et al. (1975) found a mean shift of 0.84^0 in centering the eye after straining the eyes to one side. Clearly, the bias induced by loading is similar for the tongue and eye, if judgments of position are taken following strain or following the lateral deviation of the eyes.

Larger biases have been elicited during the exertion of force in one direction (2.5^0 for the forearm, calculated from McCloskey (1973), and up to 90^0 for the eye, Skavenski et al., (1972)), and so one could speculate that eliciting judgments about tongue position <u>during</u> the exertion of force might produce a larger bias as well.

In the case of the tongue, contact with structures of the mouth, for example, the teeth, or lips, after the load has been removed could have provided information which allowed recalibration of position sense. Contact with an immovable familiar object informs one about what muscle lengths, what corollary discharges and tendon states must be achieved to attain a certain position. It is all the more surprising that a measurable bias in tongue position persists using the method of adjustment, which allowed contact with the sides of the mouth before judgment of straight ahead.

It is possible that the constant demand for precise tongue placement imposed by speech results in maintenance of lingual position sense. Likely roles for position sense include provision of a kinesthetic map of the realm of the tongue for the motor system to use in issuing speech production commands. Once calibrated, the map could be used as a basis for speech commands in the absence of feedback, thus maintaining the long term integrity of speech, as in the case of deaf speakers.

It would be difficult to account for a predictable bias in judging direction (Chapter 6) without allowing for a kinesthetic map. If there were no map, and knowledge of the motor command issued were true, then the straight ahead should have been correctly nominated. The best explanation is bias in sensed tongue position, which is registered on a map that is then used to direct movement (wrongly).

I suggest that lingual position sense is available for use in speech production. Kinesthesis should be required for vowel production, particularly for vowels such as /o/ and /u/, which involve little or no contact between the tongue and any other articulators (Bowman, 1971).

My targets in the vertical experiment have a very rough correspondence to vowel targets, in that they were in the mid-saggital plane, and taction and vision did not provide useful positional information. I have shown that kinesthetic information is available for use in non-speech lingual tasks. It is reasonable to suppose that it is also available for the motor system to use to produce speech.

The precision of tongue positioning required for speech sound production may only be estimated, in view of the lack of experimental data on this question. The best indication so far is that a standard deviation of about 1.5 mm is associated with tongue placement against the palate in the pronunciation of /s/ (Flege. Fletcher, & Homiedan, 1988).

I do not know how long the calibration remains true. One could speculate that the map is first calibrated for speech during babbling (see Borden, 1979) and can be recalibrated later as the need arises, for example, during growth of the oral cavity and the teeth. In the absence of conflicting feedback it might be years before the accuracy of the acoustic-kinesthetic cross-calibration of the map of the tongue deteriorates. This is clear from the speech of the people who have become deaf as adults. In the presence of conflicting auditory feedback, subjects can learn to rely on kinesthesis and taction to produce normal speech for at least three days (Butollo & Maly, 1967). Experiments by Weddell, Harpman, Lambley, and Young (1940), and Putnam and Ringel (1976) using anesthesia of the tongue muscle also suggest that kinesthesis is not necessary for intelligible speech production in the short term.

Speech may well be organized similarly to other motor behavior. In this respect, it may be argued that kinesthesis in the tongue could provide the spatial information prerequisite to the proper direction of the various forms of the tongue's motor activity.

CHAPTER 8

ORGANIZING SPEECH MOVEMENT

This chapter reviews the research that bears on the hypotheses from Chapter **1**, and introduces new theoretical questions about the role of kinesthesis in organizing movement.

8.1 Hypotheses

Chapter **1** proposed that speech should be organized as are body movements. The pertinent hypotheses from Chapter **1** that remain to be addressed are:

Hypothesis 2: Entrainment of limb movement

Rhythmic limb movements tend to entrain to a kinesthetic rhythm.

Hypothesis 3: Entrainment of speech movements

Speech movements tend to entrain to a kinesthetic rhythm.

Hypothesis 4: Strength of tendency to entrain

Entrainment to a sensory rhythm tends to arise without explicitly requesting subjects to entrain to the stimulus.

It is clear, based on the first half of the thesis, that kinesthetic sensation is available for at least one important speech articulator, the tongue. Now the question is whether this sensory information helps to organize voluntary speech articulator movements within a non-linear oscillatory framework. Before proceeding further, definitions of commonly used terms are required.

8.2 Definitions

8.2.1 Sensory rhythm

The source of a sensory rhythm is the temporally patterned recurrence of a perceptible quality. The temporal pattern is perceived, and the events that yield the perceptible quality are interpreted as belonging to a sequence. So when we listen to drumming, we perceive the beats as a sequence of events occurring at regular intervals. Also, we can <u>predict</u> the time of occurrence of the next events in the sequence. If we can accurately predict the time of occurrence of the next events, then it must be the case that the patterning of the previous events in the sequence was recognized and served as a basis for extrapolation of the pattern into the future. Thus, accurate prediction of future events is one test of sensing the rhythm of the events.

Body movements can give rise to a sensory rhythm. A rhythmic sequence of sounds can result from clapping; for the deaf, the rhythmic sensations would instead be those of striking the hands together. A sensory rhythm may be immanent in movement, but the important thing here is its apprehension by the senses, which allows prediction of when the next beats of the pattern will occur.

There is a strong tendency to perceive rhythm when physical isochrony (uniformity of interval between physical events) is present in the stimulus (Fraisse, 1963).

8.2.2. Rhythmic movement

The regular recurrence of physical events during movement defines rhythmic movement. For example, the attainment by a limb of its point of maximum excursion in a given direction relative to the body could be viewed as a physical event. In a rhythmic activity such as walking, the attainment of maximum excursion of the left foot (relative to the hip) in front of the body could serve as a recurring physical event, on the basis of which one could define the rhythm, or period, of walking. I am concerned specifically with recurring physical events that can be perceived or measured. In the general case, to be perceived as rhythmic, at least one perceivable physical aspect of the movement must recur at a regular interval.

The way that we currently judge the rhythmicity of movement is by sensing it. Thus, we are thrown back upon our definition of sensory rhythm (section **8.2.1**), for we look for regular perceptible events in the movement sequence, and these are what determine for us whether the movement is rhythmic. So when speaking of rhythmic movement, I do not mean to imply that the person making the movements must be aware of the patterning of her movements, or have deliberately planned them to be patterned; the judgment of rhythmicity arises from measurement by the beholder, who may or may not be the moving person, and could be a computer.

A sufficient quality to yield rhythmic movement should be isochrony of at least one recurring physical event (Fraisse, 1963). However, strict physical isochrony is not always necessary for the perception of rhythm to arise. Music can be played with rubato, or fairly loose adherence to a timekeeping beat, and still be considered to conform to the beat (Shaffer, 1982 and 1984). It is unlikely that the departures from the strict beat are random, for musicians can repeat their performances precisely, introducing elasticity into the rhythm in particular places and fashions (Shaffer, 1984). There are many complex rhythms, for example, in jazz music, but I shall restrict my enquiry to simple isochronous rhythms, as has generally been done in the field of movement study.

It should be noted that the physical circumstance that gives rise to the perception of rhythm need not be event-like or punctate in character, despite the use of the word 'event' in the definition of rhythmic movement above. People also can interpret as rhythms stimuli whose character is oscillatory, for example, a sound that alternately rises and falls gradually in pitch with respect to time.

Sequences of events that are perceived as rhythmic can arise from physical oscillation. The oscillation may be a sudden periodic alternation of two physical states, like turning a light on and off continuously, or it may be a more gradual oscillation, as indicated above. For the purpose of later experimental exposition, note that a

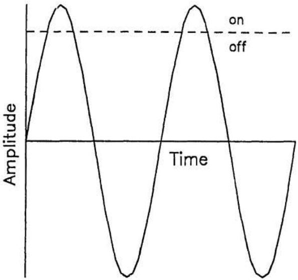

Figure 8.1. A simple oscillation. The broken line indicates the border demarcating the <u>on</u> and <u>off</u> states.

state (on or off) may be achieved during a gradual, smooth movement, as shown in Figure **8.1**. Even though the curve is smooth, it is possible to interpret it as a sequence of alternating states. The dashed cut-off line in Figure **8.1** indicates how a periodic succession of event-like movements could be derived from the smooth movement. Figure **8.2**

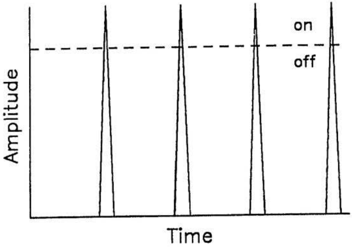

Figure 8.2. A periodic sequence of events. The broken line indicates the border demarcating the on and off states.

shows that the event-like quality is maintained when the same type of cut-off line is applied to a sequence of punctate events. The similarity

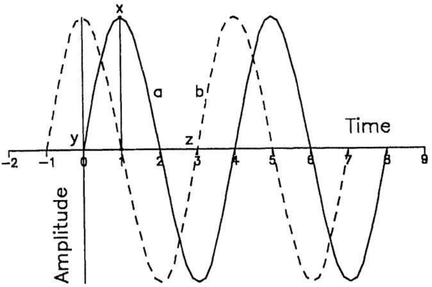

Figure 8.3 The phase angle difference (relative phase).

of interpretation of continuous and punctate data is important in the analysis of the data presented in Chapter **10**, and so is introduced here.

The terminology that will be used to describe rhythmic movement in this thesis derives from the study of periodic oscillation. The oscillation has a period (and frequency) and an amplitude. It also has a phase angle, which is the value of the abscissa corresponding to a point on the curve, relative to the period (Aschoff, 1981). In Figure **8.3**, the phase angle for X on curve A is calculated by dividing the time elapsed from the start of the cycle (X = 1) by A's period (4), yielding 25% (90°). Commonly, the phase angle is given as a fraction of the period (Aschoff, 1981). Mathematically, it is most economical to calculate proportions or percentages, so phase is given here as a percentage of the period. Thus, the phase angle difference values mentioned in Chapter **1** as being of theoretical interest, namely 0°, 90°, 180°, and 270° (relative to 360°), are presented in the rest of the thesis as 0%, 25%, 50% and 75% of the period, respectively. All measures that derive from phase angle, for example, relative phase, have also been treated as percentages for ease of mathematical manipulation and consistency's sake (see Appendix **3**: Measures).

I shall be concerned with the relationship between two oscillations, or two rhythmic movements, and so phase angle difference (relative phase in Kelso et al.'s (1981) terminology) is also important. Relative phase refers to the difference between two corresponding phase angles in two coupled oscillations. It is illustrated in Figure **8.3**.

The relative phase of curve A to curve B is calculated by subtracting the phase for a point on curve B from the phase for the same point, but relative to curve A. The phase of point Z on curve A is 75% (or 270°), since Z = 3, and the period of A is 4. Point Z is at the start of a cycle of B, and so relative to curve B has a phase of 0%. The subtraction of the two phases yields 75%, and curve B may be said to lag curve A by 75%. It should be noted that the value of -25% (-90°) may also legitimately represent the relative phase here, as curve B could also be said to lead curve A by one quarter of A's cycle. The method of calculating relative phase for the experimental data is given in Appendix 3.

8.2.3 Rhythm in language

It has been remarked that many stress-timed languages, like English, display rhythmic properties (Lehiste, 1977). These rhythmic properties of language shall not be discussed further here. From the point of view of the thesis it is important that movements of the speech articulators provide evidence of non-linear oscillatory organization; the particular biological function of those articulatory movements should not preclude the marshalling of non-linear oscillators to organize the movements. Rhythm in fluent spoken language does not necessarily concern the thesis closely because the thesis is not primarily interested in communicative functions. The analogy between limb movement and speech articulator movement that is at the heart of the thesis may not be properly maintained if language with its overriding communicative function dictates the form of the speech used here.

Rhythm in normal, fluent spoken language is nonetheless intriguing in that normal speech is perceived as rhythmic in some respects, despite the fact that it has a communicative function. Arguably, communication might not be served especially well by the presence of predictable, and therefore, potentially informatively redundant, rhythmic movement. In sum, the existence of rhythm in fluent spoken language could support the thesis, but is not crucial to the main analogy.

8.2.4 Entrainment

When an oscillating object is coupled to another oscillating object (the driver) and the two come to move at the same frequency, or one object moves at a frequency that is an integral multiple of the other's frequency, then the objects may be said to show entrainment (Aschoff, 1981). Figure **8.3** provides an example of entrainment of two oscillations whose relative phase is 75%. Typically, entrainment in biological systems has been found within a limited range of frequencies (see Chapter **9**).

8.3 Review of Past Work on Sensory Influences on Rhythmic Movement

The hypotheses presented at the beginning of the chapter can now be discussed in light of the literature.

8.3.1 Kinesthetic influences on rhythmic limb movement (hypothesis 2)

Past research has shed relatively little light upon the hypothesis that voluntary rhythmic body movement entrains to a kinesthetic rhythm. It is becoming clear from work on non-human animals that afference can drive rhythmic movement (eg. Rossignol et al., 1988; Katz & Harris-Warwick, 1990). However, the research on the influence of kinesthetic sensation in producing rhythmic limb movements in humans is ambiguous. The main problem is the failure to separate motor influences from purely sensory influences, which is referred to here as the sensory-motor confound.

In experiments on entrainment, commonly the subjects may be observed to move two limbs voluntarily in phase and they find it difficult to do otherwise (eg. Kelso et al. 1979; Kelso et al., 1981; Klapp, 1981). It is not clear whether the observed entrainment of the two limbs' movements is purely motor, that is, whether the motor plan is directing the limbs as one unit, while ignoring the kinesthetic information that arrives at the brain from the moving limbs. The kinesthetic information is also a potential driver for the limb movements.

A punctate kinesthetic rhythm should arise when tapping the finger against a surface, for tapping gives rise to a clear sensation of contact, and finger tapping has commonly been one of the tasks in experiments on rhythmic movement (Ehrlich, 1958; Klapp, 1979; Klapp, 1981; Klapp et al., 1985; Smith et al., 1986; Hary & Moore, 1987). Tapping adds the signal from a punctate event to the array of kinesthetic information that is sent to the brain. This sensory-motor confound marks the work on simultaneous limb movements even when no tapping is involved, as in work by Kelso et al. (1981) and Scholz and Kelso (1989 and 1990). Normal movements elicit spindle firing in the muscles, and so give rise to afferent kinesthetic messages to the brain. Cutaneous and spindle afferent information could be employed by the brain to drive the rhythm of the movements.

The solution to this dilemma would be to provide (external) rhythmic sensory information that conflicts with the internal rhythmic kinesthetic information arising from movement. If the rhythm of the externally introduced conflicting sensation is adopted, then sensation (whose source is external) can be said to drive movement rhythm, and kinesthetic information arising from one's own voluntary movement will not be the sole sensory driver of movement rhythm.

The separation of sensory and motor would be valid even if the conflicting externally supplied rhythmic sensory information is introduced kinesthetically. The main point is that unless the externally imposed sensory rhythm conflicts with the internal kinesthetic rhythm, it is not possible to judge whether it is the motor side of the human motor plan that drives the movement rhythm, or whether sensory information might be partly responsible for the patterned movement. Interpretation of much otherwise potentially relevant work (eg. work by Klapp and Kelso and their coworkers) is handicapped by this ambiguity of interpretation. In sum, it is not clear whether the non-linear oscillatory character of movement is forged solely by the motor side of the motor plan or by sensation as well. To address this problem, a stimulus rhythm that continuously changes, taking a trend different to that which the subject prefers, could serve experimentally. If it induces entrainment of the subject's rhythm, then one may claim that entrainment characterizes the organization of movement.

The second problem with studies of entrainment of limb movements is that the experimenters commonly request as part of the experimental task that the subjects synchronize the movements of one limb to an external rhythm (eg. Klapp, 1979; Klapp et al., 1985; Hary & Moore, 1987; Scholz & Kelso, 1989 and 1990), or to movements of another limb (eg. Kelso et al., 1981). It is not possible to conclude that sensation is normally or necessarily relevant to motor organization if subjects have been specifically instructed to make it relevant. It is conceivable that rhythmic kinesthetic information might be ignored by a movement planner, particularly if the information can be viewed as irrelevant to the success of the current movement. A convincing argument for a necessary role for kinesthetic rhythm in movement organization can be put forward only if kinesthetic rhythm is consulted either a) when it conflicts with the purpose of the subject, or b) when it is irrelevant to the success of the movement. It is for these reasons that hypothesis 4 was introduced into the thesis.

8.3.2 Kinesthetic influences on rhythmic monosyllabic speech movements (hypothesis 3)

Very little unambiguous information speaks to the hypothesis that speech movements entrain to a kinesthetic rhythm. The most informative work in this area has been conducted by Smith, McFarland and Weber (1986). Nonetheless, the same motor-sensory confound (see section **8.3.1**) that pervades the work on limb movement organization also marks work on speech articulator organization, including that by Smith et al. Experiments that require subjects to repeat a monosyllable while moving a limb at the same (or at a harmonically related) frequency cannot separate efferent and afferent (kinesthetic) influences on movement organization (eg. Smith et al., 1986), as explained above with reference to limb movement (section **8.3.1**).

Nonetheless, if it can be shown that a limb and the speech articulators can be moved simultaneously at different rates, then we have a strong argument against the <u>necessity</u> of non-linear oscillatory organization, in either the motor or the sensory part of the movement system. There is no evidence of this from unpractised subjects making simultaneous limb movements (see section **8.3.1**), but the conclusion is less firm when speech articulators are the moving parts.

Smith et al. (1986) and Kelso et al. (1983) have requested that their subjects repeat a monosyllable and move their finger at <u>different</u> rates. Kelso et al. (1983) claim that their subjects entrain under these conditions, while Smith et al. (1986) remark that there is a tendency to entrainment, with the rate of preferred monosyllable repetition being maintained, and the preferred rate of finger movement changing to that of the speech (or to its multiples).

In fact these remarks are open to argument. In Kelso et al.'s (1983) Figure 7-10 , the synchronization of speech to finger movement is not clear, and the ratio of events is between 4 and 5 syllables to 1 finger movement cycle. It is clear from Smith et al.'s data that the ratio of the period of syllable repetition to that of the finger movements tends to be fairly close to a perfect integer ratio, which is often other than 1:1 (synchrony), for example 2:1, 3:1, and even as high as 7:1, but is not usually a perfect integer ratio. Smith et al. suggest quite appropriately that the coupling of the speech articulators to the finger can be weak. This is the most relevant piece of information that the literature provides with respect to the nature of the entrainment that can be expected to arise in the speech experiments here.

The rate of speech is possibly not maintained as strongly as Smith et al. (1986) suggest, once simultaneous finger movement is begun. Table 2 in Smith et al. (1986) shows 3 of 8 subjects preserving their monosyllable repetition rate rather than their finger movement rate (or one of its multiples). The remaining 5 cases show considerable change in both finger and speech rates.

It is worth remembering that in an assembly of non-linear oscillators, we should not expect fixed dominance from one moving system, such as the speech articulators (Kelso et al., 1983). We might expect the <u>function</u> of the movement to dictate which moving parts should set the preferred rate, with the (temporarily) most important function setting the rate to which other moving parts become entrained. If this is so, then provided that the function of speech is not viewed by subjects as more important, the rate of speech should be changeable in such synchronization experiments.

There have been no explicit tests of kinesthetic influences on speech rhythm, although Fry (1966) claimed that kinesthesis had a major role in controlling the timing of speech movements.

8.3.3 Relative phase of kinesthetic rhythm to movement

Results from the literature tend to bolster the relative phase relationships that characterize simultaneous limb movements (eg. 0% and 50%: Kelso et al., 1979; Kelso et al., 1981; Kelso, 1984; Scholz & Kelso, 1989 and 1990).

With respect to simultaneous monosyllable repetition and limb movements, the most thorough paper in the field, by Smith et al. (1986), showed more variable relative phase values and Figure 7-10 of Kelso et al.'s work (1983) on this topic does not clearly show entrainment, and so detracts from Kelso et al.'s claims about standard phase values (eg. 0% and 50%). There appears to be a very strong tendency for simultaneous limb movements to be synchronized (that is, to show 0% relative phase); the evidence is somewhat weaker for monosyllable repetition and finger movements, but is still evident.

With respect to the main thesis, there is in any case no clear evidence about which phase relationships should be expected if a kinesthetic rhythm alone drives voluntary limb or speech movements (see section **8.3.1**).

8.3.4 Other sensory influences on rhythmic limb and speech movements

There are no studies on the influence of externally introduced kinesthetic rhythms on organizing voluntary movement. The only information available comes from experiments using other sensory rhythms (other than kinesthetic). On logical grounds (see section **8.3.1**) a sensory rhythm that conflicts with the subject's movement rhythm is required to address hypotheses 2 and 3. What we know about other sensory rhythms that conflict with the subject's rhythm of movement may suggest by way of analogy what to expect if a kinesthetic rhythm is externally introduced.

Tasks are carried out more successfully by humans if external sensory information and consequent voluntary movement may be organized on a cycle. Humans can press keys and repeat syllables such that the speech sounds and the key presses are in phase with two simultaneously presented sequences of external sensory stimuli whose frequencies are harmonically related, for example, sequences of visible lights and audible tones (Klapp, 1979 and 1981; Klapp et al., 1985). In contrast, people have difficulty performing the same tasks if the external sensory stimuli have unrelated frequencies (Klapp, 1979 and 1981; Klapp et al., 1985).

The disharmonious frequencies have a deleterious effect on perception. Recurring sensations arising from external events are most efficiently interpreted if they can be organized on a cyclic basis (Klapp et al., 1985). We might then infer that movement might be most easily planned if the bases, both sensory and motor, for all limbs were harmonically related.

Studies on perturbation of rhythmic movements are germane to the thesis. However, they do not directly address the hypotheses here, for one cannot judge whether sensation drives a process in the normal case by observing that sensation may disrupt it. Nonetheless, experiments that perturb subjects' movement offer valuable evidence that speech movements are organized similarly to limb movements, and they indicate non-linear oscillatory principles for both movement types.

Studies of perturbation introduce a sudden unpredictable resistance to the rhythmic movement of one of two synchronized limbs (or speech articulators). The pattern of movement of the other (<u>untreated</u> and synchronized) segment is also disrupted, usually on the same or the following cycle of movement (Folkins & Abbs, 1975; Kelso et al. 1981; Scholz & Kelso, 1989). Here the disruption is both sensory and physical. These results show that entrainment may be disrupted and reasserts itself, as could be expected in a non-linear oscillatory system (see section **1.5.2**)

It has been claimed that the anomalous movement by the non-treated limb may be a form of compensation for the unsuccessful planned movement by other perturbed limbs in the synergy; this conceivably might arise when movement cannot be conducted as planned in a non-linear oscillatory system and the energy required to overcome a physical impediment by the stopped limb is also gated through to other limbs in the same synergy (see Folkins & Abbs, 1975;

Kelso & Tuller, 1983; Tye, Zimmerman & Kelso, 1983).

This motor explanation receives some support from Craske & Craske (1985 and 1986), whose findings imply that oscillatory processes can be directed to other, previously unmoving, limbs in a synergy by directing one's attention appropriately. Gating of energy to a limb that is already moving should be possible, given that oscillation can be transferred to a non-moving limb.

It is plausible also to suppose that the kinesthetic afference arising from the physical perturbation might elicit predictive adjustment to the movement commands to the unperturbed limb, possibly at a low level in the motor system, since recovery from disturbance to posture is known to be fast (Cordo & Nashner, 1982; Abbs, Gracco & Cole, 1984). The motor plan allows for fast reactive correction to motor commands to a limb, and in principle, should simultaneously allow predictive adjustment to the commands to move the next limb in the planned sequence (see Figure **1.3**, Chapter **1** and accompanying discussion).

Work on posture would lead one to expect fast predictive adjustment to be possible (eg. Cordo & Nashner, 1982). In many everyday circumstances, predictive adjustment would be very useful, for example, if a person stumbles with one foot against a step, the other foot should not stumble against the step as well, resulting in the body falling to the ground. However, the fact remains that more than one explanation for the pattern of recovery from experimental physical perturbation exists, one motor, one afferent, and one that is both motor and afferent.

The results from perturbation studies on mandible movements (eg. Folkins & Abbs, 1976), simultaneous monosyllable repetition and finger movement (eg. Kelso & Tuller, 1983), and simultaneous finger movements (eg. Kelso et al., 1983) are similar. They are valuable here, for they show that rhythmic limb and speech articulator movement are similarly disrupted by, and recover from, perturbation. Those findings uphold the central thesis that speech movement and other voluntary body movements are organized similarly using non-linear oscillatory processes.

8.3.5 Summary of evidence about the main hypotheses

The main evidence is this: subjects find it difficult to move two limbs simultaneously, or a limb and the speech articulators, unless the movements have the same period, or one segment's period is a multiple of the other's. The entrainment should have a sensory basis, given Klapp et al.'s (1985) finding that subjects find it easier to monitor two sequences of stimuli if they can be organized on a cycle. Currently, most experimental reports intertwine sensory and motor contributions to motor organization, and commonly further confound the interpretation of results by instructing subjects to make externally supplied sensory information relevant.

No experimental results have been found to contradict the hypotheses, yet the data from the most reliable experiment on simultaneous monosyllable repetition and finger movement (eg. Smith et al., 1986) unmistakably suggest that the coupling of speech movements to finger movements is not as powerful as the coupling of finger to finger movements. It should be the case in a non-linear oscillatory system that simultaneous movements are synchronized within a certain range of frequencies; that is the crucial criterion in the classification of a moving system as having a non-linear oscillatory character, questions of sensory or motor bases aside.

It is possible that people award speech the greatest importance, even if it temporarily serves no communicative function, as would be the case in Smith et al.'s experiment. Then it might be the case that people would tend to preserve the speech rate and not allow speech to synchronize to limb movements. This is a good reason for requesting from subjects speech and limb movement in isolation, rather than simultaneously, given that the two functions might potentially compete for consideration as 'most important function', and thus the function to preserve unchanged, relative to performance in isolation.

8.4 The Driving Sensory Rhythm

The hypotheses present new questions. It is not known what factors would permit a sensory rhythm to impinge upon the rhythm of movement. The modality of the sensory information relative to the function of the movement might or might not be important. If one is monitoring the products of one's own movement, for example, listening to one's own piano playing, an external rhythm of sound, different from the rhythm that one is playing, introduced into the auditory (monitoring) channel would seem to be a more plausible candidate for modifying the movement than would be the same external rhythm introduced into some other sensory modality. The incompatible rhythm is relevant in that it usurps a channel normally important to success at the task at hand, performance at the piano. The relative effects of presenting in different sensory channels sensory information that competes with, or replaces, the feedback from a concurrent motor task are not known.

Studies of disruption of rhythm provide pertinent information although they do not specifically address the hypotheses about entrainment (see section **8.3.4**). Certainly, feedback in a relevant channel leads to interference in organizing movement. The debilitating disruptions in speech that ensue upon hearing one's own speech at a delay of about 200 ms (delayed auditory feedback; see Fairbanks,

1955) may be pervasive because disruptive feedback about speech rhythm is presented in a relevant modality. We perceive speech by ear, and the function of speech is to communicate by sound, which of course is also perceived and monitored aurally. Had the rhythm of the subjects' speech been presented to them in a different modality, for example, as variations in the intensity of light, there might have been less disruption of the rhythm of their speech.

Very little has been proposed about the essential qualities that a sensory driver might have, if one exists. I suppose that entrainment should be induced by certain qualities of the kinesthetic rhythm, in accordance with the remarks in section **8.2.2** above. Two hypotheses can be formulated.

8.4.1 Hypothesis 5: Punctate character of stimulus

Past experiments have commonly used a simple, event-like stimulus, like a metronome (eg. Klapp, 1979 and 1981; Hary & Moore, 1987; Scholz & Kelso, 1989). This clean temporal character may be an essential ingredient in driving a motor rhythm. Kinesthetic afference is probably not always tidy in this way. While contact with the skin may be punctate or continuous, the afference from the moving limb is not likely to have an on/off character.

Hypothesis 5

If the temporal pattern of the driving rhythmic movement must comprise clearly delineated punctate events, then kinesthetic sensations arising from a continuous brushing backwards and forwards over the skin should be a less successful driver than the kinesthetic sensations arising from a sequence of sudden taps on the skin.

8.4.2 Hypothesis 6: Sources of stimulus afference

If afference from more numerous sources is present, then more sensation should result. The sensation might be more intense, or more convincing than if the afference arises from a single source, and so be a better driver.

Hypothesis 6

A stimulus that elicits afferent information from numerous sources should more forcefully drive the rhythm of a movement. Forceful drive could result in long-lasting adherence by the moving subject to the stimulus rate, or entrainment directly in or out of phase.

8.5 Conclusion

This chapter has reviewed the literature and formulated the hypotheses to be tested. Chapter **9** presents the hypotheses in experimental terms, Chapter **10** describes the methods used to test them, and Chapter **11** the results. Since the experiments are methodologically similar, and comparisons between their results important, it seemed more sensible to present them together, rather than devoting a chapter to each, as was done with the experiments in the first half of the thesis.

CHAPTER 9

EXPERIMENTAL FORMULATION OF ENTRAINMENT HYPOTHESES

The main aims of this chapter are to convert hypotheses 2 to 6 into a form that will permit experimental investigation and numerical analysis of the data that arise.

9.1 Experimental Formulation of Hypotheses 2 and 3 (Entrainment) and Consideration of Relative Phase

It is appropriate to consider the effect of a rhythmic kinesthetic stimulus with a continuously changing period upon a subject's concurrent production of speech or limb movement at a rhythm that he prefers. This avoids the pitfalls outlined in Chapter 8. The kinesthetic stimulus rhythm should generally conflict with the subject's preferred period of movement, and be irrelevant to the success at completing the movement.

The logic behind the experiments is as follows: a rhythmic kinesthetic stimulus should cause the subject to change his limb or speech movements such that they entrain to those of the stimulus, or to a submultiple or multiple of the period of the stimulus cycle. Showing that the subject's preferred period changes as predicted, namely, as the period of the stimulus movement changes, should be the clearest evidence of effect. This implies that the subject must have established a preferred period of movement before the stimulus, which has a different period, is introduced.

Now it is time to consider what should constitute evidence of entrainment, and what should not constitute evidence of entrainment. I shall present the argument in terms of periodic subject and stimulus movement; the theoretical argument in terms of the actual tasks and stimuli used would be identical.

9.1.1 Graphical presentation of hypotheses 2 and 3 (entrainment) and of the question of relative phase

First, the subject's mean period of movement should become very similar or identical to that of the stimulus after a certain period of exposure to the stimulus, and remain entrained for some time. To ensure that the subject's preferred period of movement differs from that of the stimulus, the stimulus period can be made to change continuously, following a trend opposite to that of the subject. The demonstration of entrainment will be fortified if the subject's movements remain entrained even though the stimulus period changes. This is represented by the transition in the subject's period from time (b) to time (c) to time (d) in Figure 9.1.

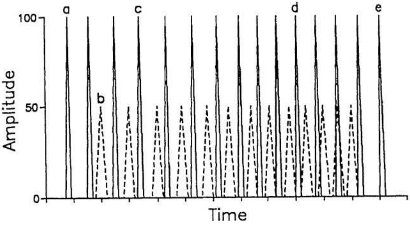

Figure 9.1. Amplitude versus time plot of subject movement and stimulus movement showing entrainment. Solid line: subject movement. Dashed line: stimulus movement. (a): subject establishes a preferred period of movement. (b): stimulus begins to move. (c): subject begins to entrain to stimulus rhythm. (d): subject ceases to entrain. (e): subject continues to move, establishing a (new) preferred period.

Figure **9.1** shows that after time (b), the subject is abandoning the period initially preferred at (a), and is slowing down in the presence of the slower stimulus. By point (c), the subject and stimulus period are becoming similar, and at the time halfway between (c) and (d) the relative phase stabilizes at 50%. The subject's period continues to change with the stimulus period up to point (d), when the subject period remains unchanged, as the stimulus speeds up. After stimulation stops, the subject continues to move his finger until the preferred period has again stabilized (e). We should consider the behavior between (b) and (d) to show a tendency to entrainment.

A few words should be added about the format of Figure **9.1**, for many of the graphs in the remainder of the thesis take this form. The data are presented in similar form to those in Figure **8.2**. The period can be calculated as the interval between two successive peaks (see Enright, 1981). In terms of movement, the peaks could represent maximum excursion; for example, the peaks in the subject's movement could stand for the bottom of the swing of the subject's finger (solid line peaks), and the peaks in the stimulus movement for the bottom of the trajectory of an object (a solenoid) that taps on the skin of the arm (dashed line peaks). The peak would be shown as occurring at the time at which the solenoid makes contact with the arm. Thus, both continuous movement, such as swinging the finger, and stimulus movement that is experienced by the subject as punctate, such as the descent of an object to tap briefly on the arm, can be represented similarly and adequately for the purposes here. The method of picking peaks from continuous data is described in

Appendix 2.

In the graphs of this chapter the units of time and amplitude are largely arbitrary, and have been included only to make the derivation of

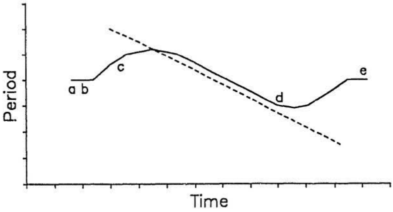

Figure 9.2. Mean period versus time plot of the data shown in Figure 9.1. Solid curve: subject's movement. Dashed curve: stimulus movement.(a): subject's preferred period has been established. (b): the stimulus has commenced, and the subject's period is beginning to lengthen. (c): subject begins to entrain to stimulus rhythm. (d): subject begins to abandon entrainment. (e): subject establishes a (new) preferred period.

the period-time graphs from the amplitude-time graphs more transparent.

The information in the amplitude-time graph of Figure **9.1** can be more compactly represented in a period-time graph, as Figure **9.2** shows. The period of the subject's movement alters under the influence of the stimulus movement within a limited range of periods. Mean period versus time plots will commonly be used for data presentation in the remainder of the thesis. In Figure **9.2** the subject period values in the middle section of the graph appear to lag those of the stimulus slightly. This was done to show the two trends more clearly, and is not a theoretical necessity.

Figures **9.1** and **9.2** illustrate the confirmation of hypotheses 2 and 3. A rhythmic stimulus induces the subject to change the preferred period of her movement such that it becomes more similar to that of the stimulus. Moreover, the relative phase of the stimulus and subject movements is stable.

9.1.2 The null hypotheses for hypotheses 2 and 3 (entrainment)

Now it is necessary to have a clear idea of subject behavior that could refute the hypotheses of entrainment. There are several obvious possibilities. If the subject's rate of movement does not change as predicted upon exposure to a stimulus with a contradictory rhythm, then it would be plain that entrainment was not occurring. This is shown in Figure **9.3**. Either the subject maintains her initial rate (curve a), or her period of repetition continuously shortens (curve b) as that of the stimulus (curve c) lengthens.

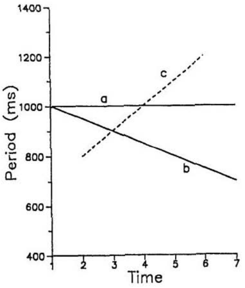

Figure 9.3. Plot showing lack of entrainment between subject and stimulus movement. Curve a: subject's preferred period does not change in the presence of a stimulus. Curve b: subject's preferred period takes the opposite direction to the stimulus period. Curve c: stimulus period.

Figure 9.3 represents a number of important points. First, the mean periods of the subject and stimulus movements do not stand in an integer relationship, except by chance. This can be readily seen from the ratios of the subject to stimulus period in Table **9.1**, which represents the graphical

Table 9.1 Ratio of stimulus to subject period for the data in Figure 9.3.

Time	Stimulus Period (c)	(a) Period	(b) Period	(c:a) Ratio	(c:b) Ratio
1	-	1000	1000	-	-
2	800	1000	950	0.8:1	0.8:1
3	900	1000	900	0.9:1	1:1
4	1000	1000	850	1:1	1.2:1
5	1100	1000	800	1.1:1	1.4:1
6	1200	1000	750	1.2:1	1.6:1
7	-	1000	700	-	-

Note. The letters (a), (b) and (c) refer to the curves in Figure **9.3**.

information of Figure **9.3** numerically. Perfect integer relationships characterize entrainment. Thus, hypothesis 2 (or 3), about entrainment, is met in only one sample of five. Moreover, the relative phase is unstable. If the subject and stimulus movement periods are not the same, their relative phase will vary. Figure **9.3** then demonstrates a first step in formulating the null hypotheses for the major hypotheses 2 and 3: If the mean period of the subject's movement does not change to become similar to that of the stimulus, then entrainment has not occurred (see section **8.2.4**). If entrainment does not occur, a stable relative phase cannot arise either.

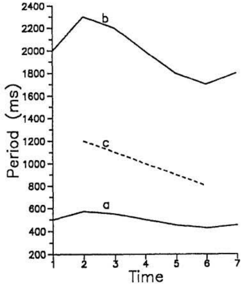

Figure 9.4. Theoretical submultiple and multiple cases. a: subject's period (half that of the stimulus). b: subject's period (double that of the stimulus). c: stimulus period.

9.1.3 Submultiple and multiple relationships

Submultiple relationships between the subject and stimulus periods might also arise and should count as examples of legitimate entrainment. Two such cases are shown in Figure **9.4**. The subject might entrain at double (curve b) or half (curve a) the stimulus period (curve c). As these multiple integer ratios of periods are theoretically possible, but have been reported only occasionally in the literature (eg. Kelso et al., 1983; Smith et al.,1986), they are probably less common than the 1:1 entrainment shown in Figures **9.1** and **9.2**.

9.1.4 Mean period versus frequency or amplitude

I have presented the hypotheses in terms of periods in order to preserve in a transparent way the presence of time wherever possible in the exegesis. Other workers, namely Smith et al. (1986), have presented their research in terms of frequency, or as amplitude variation over time (eg. Kelso et al, 1981; Kelso et al., 1983). Amplitude versus time is not economical, particularly for graphical presentation, as is evident from a comparison of Figures **9.1** and **9.2**. Frequency involves conversion of time to its inverse, and so is a less transparent measure.

9.1.5 Assumptions about variablility of the period

The forfeiture of the detail in amplitude-time plots in favor of mean period values has a price, namely, blindness to variability. The crucial assumption here is that the mean period of the subject's preferred period of movement does not vary greatly. Unless this assumption is upheld, the mean period and the mean relative phase are misleading measures, as

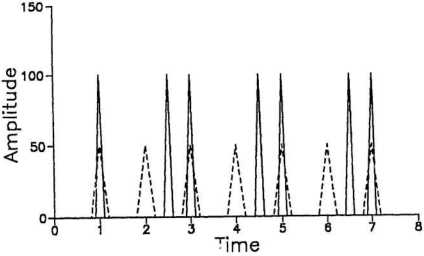

Figure 9.5. Case of lack of entrainment that would yield mean periods for subject and stimulus movement and a mean relative phase wrongly implying entrainment. Solid curve: subject movement. Dashed curve: stimulus movement.

Figure 9.5 demonstrates. It is possible for the subject's period to vary greatly, producing a mean period value identical to that of the stimulus movement, and a mean relative phase of 25%, as Table **9.2** shows.

Table 9.2. Mean periods and relative phase values for the data shown in Figure 9.5

Order of Interval	Period		Relative Phase (%)
	Stimulus	Subject	
1	1	1.5	50
2	1	0.5	0
3	1	1.5	50
4	1	0.5	0
5	1	1.5	50
6	1	0.5	0
Mean	1	1.0	25

Note. Order: order in the sequence of completed peak to peak intervals. The phase of the final peak in each interval of the subject's data is given relative to the enclosing stimulus period (see Appendix **3**) in the relative phase column.

In Table **9.2,** the relative phase represents the time of occurrence of the peak in the subject's movement relative to the period of the stimulus data. It can be seen from Figure **9.5** that the peaks in the subject movement occur alternately perfectly in phase (0%) and perfectly out of phase (50%) with the stimulus peaks. The perfect integer relationship between the mean periods of the subject and stimulus data over the full sample, and the mean relative phase of 25% would lead wrongly to the conclusion that the subject had entrained to the stimulus in the predicted way. Further details of relative phase and variance calculations are given in Appendix 3. In consequence, it will be necessary to verify that the variability of the period of the subject's movement is low, and that the relative phase does not pattern in this way, before considering the null hypotheses.

9.1.6 Expected range over which entrainment occurs

There are still a number of ambiguities to be resolved. How does one know the range of periods within which to expect entrainment ? Smith et al. (1986) set their limits arbitrarily. If their subject's preferred frequency of movement changed to be within 25% that of the stimulus, the data were counted among the evidence for entrainment. On the other hand, Wendler (1974) showed that by driving one of a locust's wings externally, one could drive the rhythm at which a locust beats its remaining wings, but only within 15% of the preferred frequency of wing beating.

Enright (1981) points out that decisions made by researchers in this field about what constitutes acceptable variability about a summary measure of rhythmic behavior are largely arbitrary. This point also holds good for decisions about the expected range within which entrainment should occur, although Enright does not go so far. The decisions about the expected range of the stimulus period that can induce entrainment are usually based upon observation and common sense (eg. Kelso et al., 1981; Smith et al., 1986; Scholz & Kelso, 1989 and 1990). I shall adopt the range of ±15% of the subject's preferred period as the approximate range over which entrainment is to be expected, as this is conservative with respect to the range over which entrainment was said to occur in the literature that is closely relevant to the work here (ie. Smith et al., 1986), and also seems appropriate on intuitive grounds.

To be certain of determining the limits of the range of entrainment it was advisable to start the stimulus at a period outside of ±15% of the subject's preferred period. Figure **9.2** shows the initial stimulus period to be longer than the subject's by 20% of the subject's preferred period.

9.1.7 Control conditions

The natural tendency of the subject's movement is also a matter of concern. Subjects' preferred periods of movement may change naturally over time, even in the absence of experimental manipulation. Accordingly, a control condition was required to capture the subjects' preferred rate over the time that the experiment would take.

The trend of the subject's preferred period of movement can be said to be influenced by the stimulus period only if, in absence of the stimulus, that trend fails to appear. Not only must the subject's preferred period be seen to change in a predictable fashion in the presence of the stimulus, but the preferred period must fail to change in that fashion in the untreated case. Figure **9.6** illustrates this type of possible failure to entrain.

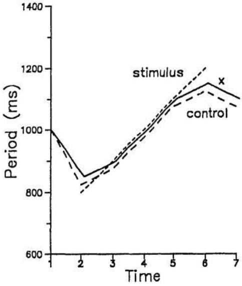

Figure 9.6. Case of lack of entrainment: congruent control and experimental data. x: (experimental condition) subject movement in the presence of an external stimulus. short dashes: the stimulus movement. long dashes: (control condition) subject movement in the absence of an external rhythmic stimulus.

Although the trend in the subject's preferred period of movement leaves the impression that entrainment has occurred after comparison to the stimulus period (curve x versus the stimulus curve), it is apparent upon inspection of control data gathered in absence of external stimulation, that in fact the subject might not have been influenced by the stimulus at all. The control condition then serves as a baseline. Thus, a second null hypothesis with respect to hypotheses 2 and 3 can be formulated: If there is no difference in the trend of the subject's preferred period of movement in the presence and in the absence of an external stimulus, then entrainment has not occurred.

In section **8.3**, it was argued that any externally imposed rhythm should initially conflict with the subject's movement rhythm if subsequent synchronization of subject and stimulus movement is to be taken as proper evidence of entrainment. To ensure that subjects adopted a movement rate that was not influenced by the experimental sensory rhythm, subjects needed to be permitted to settle on a preferred period before the externally supplied rhythm began. Initial intervals thus were required, during which subjects should not be exposed to an external rhythm, but would nonetheless move at their preferred period. These intervals may be viewed as control trials that accompany each experimental trial.

The first interval permitted the subject to settle on a preferred period of movement and allowed the experimenter to observe the subject's period and consequently to set the stimulus period to be different from the subject's. A similar final interval was also introduced. It allowed the experimenter to compare the change in the subject's period in the absence of a stimulus rhythm in the experimental and control conditions. This was not specifically required by the hypotheses or in light of previous literature, but was considered potentially useful, should unusual behavior be exhibited.

9.1.8 Advantages of a gradually changing stimulus period

Also important to testing the hypotheses was a gradually changing stimulus period. Entrainment in its fullest sense is a continuous coupling of two movements. Uninterrupted adherence to a *changing* rhythm is the most forceful evidence of the continuous nature of coupling. The adoption of an external frequency that is presented in increasing or decreasing steps (eg. Scholz & Kelso, 1989 and 1990) is a less sensitive indicator. The subject might *choose* to change her movement rate when she is alerted to the noticeable stepwise change in the stimulus rhythm, and otherwise be uninfluenced by the rhythmic sensation. Then we could conclude that entrainment is not *necessary*, only *voluntary*.

However, if entrainment is only voluntary and the change in stimulus period is very gradual, then a lapse of attention on the subject's part should result in her movement rate showing a plateau as the stimulus rhythm changes. Thus, using a gradually changing stimulus period I should be able to discriminate more surely the degree to which entrainment is fundamental to the organization of movement. If entrainment occurs when the subject does not attend closely to the stimulus, a good case can be made for non-linear oscillation as an important factor in the organization of movement.

Further, gradually changing the stimulus period should more precisely show the limits of the range of entrainment than changing the stimulus period in steps may do.

9.1.9 Enhancing the contrast between the null and alternative hypotheses

The inclusion of a control condition enhanced the contrast between alternative and null hypotheses. Evidence in favor of the alternative hypotheses would be all the more powerful, if the subject entrained to the stimulus when the trend of the stimulus period took the opposite direction to the subject's natural trend. The experimental stimulus period was purposely altered in the opposite direction to the subject's natural trend in the control condition in order to demonstrate treatment effects more transparently. So, if a subject tended to slow down overall during the control condition, during the experimental conditions, the stimulus sped up. Thus, the data from an entrainment experiment should take the form shown in Figure **9.7**, if entrainment occurs, and the form shown in Figure **9.8**, if entrainment does not occur. In Figure **9.7** the subject's period in the experimental condition follows that of the stimulus closely,

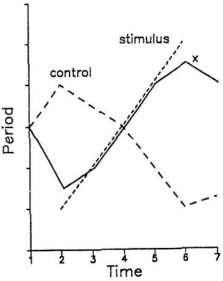

Figure 9.7. Data confirming the experimental hypotheses. long dashes: control condition. short dashes: stimulus. x: experimental condition, subject movement.

and contrasts sharply with that of the control condition, while in Figure 9.8 the subject's period mimics that of the control condition, and does not follow the stimulus trend.

There is no guarantee that subjects will produce a linear control trend, or even the same curvilinear trends. In Figures 9.7 and 9.8 the

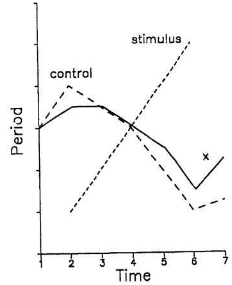

Figure 9.8 Data confirming the null hypotheses. long dashes: control condition. short dashes: stimulus. x: experimental condition, subject movement.

control trends have been shown as curvilinear, because generally there are changes in the direction of the trend of the period across samples, even though overall, a consistent direction (lengthening or shortening of the period) is plain. It is not possible to specify the trend of the subject's period in the control condition a priori. In consequence, the control trends shown in the figures of this chapter are fundamentally arbitrary. They are presented because they illustrate important possible and probable trends, based on pilot work.

It is worth noting that a limiting control trend for any experiment is a horizontal line. I speak of the control trends as having a direction (see section **9.2.3**). Direction is determined by the difference between the subject's initial and final period in the control condition. If the subject's final period is shorter than her initial period in the control condition, then the direction of the control trend is referred to as downward, and the stimulus period will be set to lengthen over the course of the experiment. If the final period is longer than the initial period, then the stimulus period will be made to shorten over the experiment. Thus, a value of no difference between initial and final subject periods in the control condition is the limiting value for a control trend, given a stimulus that takes a particular direction (lengthening period, for example). This is represented as a straight line where relevant (for example, in Figure **9.9**).

9.2 Numerical Formulation of Null Hypotheses about Entrainment

Let us now give numerical form to the null hypotheses about entrainment (hypotheses 2 and 3). I shall refer to the case where the stimulus and subject period are of the same order, but the arguments also are valid for submultiple and multiple relationships.

It is well worth noting that statistical tests for the existence of entrainment do not exist in the behavioral literature (eg. Kelso et. al., 1983; Smith et al., 1986; Baldissera, Cavalleri, Marini & Tassone, 1991). Smith et al. (1986) present mean frequency ratios and their standard deviations (per subject per experiment), a practice similar to that which I shall follow in the Results section (Chapter **11**), except I use a measure based on period ratios. They do not conduct any inferential statistical tests on their data, because the data are not susceptible to such tests. The problems with variability that I encounter in this area are similar to theirs, and I outline them below.

While Kelso and co-workers conduct inferential statistical tests (eg. Kelso et al., 1981; Scholz & Kelso, 1989 and 1990), they instruct subjects to adopt a particular pattern of entrainment to a stimulus (their control condition), administer a treatment, and then look for changes in the pattern. By instructing subjects, they eliminate the potential variability that is problematic here, and so are in a better position to conduct inferential tests, but at the same time they have lost the logical ground for claiming that entrainment is natural, rather than forced, a sacrifice that I am unwilling to make.

Other authors have presented their data as frequencies, whereas I present periods. There is a some difference between dealing with a number and its inverse, but no researcher has claimed that frequency, rather than period, must be the relevant measure. Consider Wendler's (1984) figure of ±15% for the range of frequencies over which entrainment occurs. A subject with a preferred period of 1000 ms moves at a frequency of 1 Hz; 15% of that defines a range from 0.85 to 1.15 Hz. This range translates to a range in period of 1176 ms to 869 ms (1000 + 176, -131 ms). The resulting average deviation about 1000 ms is 153 ms. The range of ±15% of the period would be 1000 ms ±150 ms, which is virtually identical to the average deviation in frequency of ±15% about 1 Hz. I have chosen a symmetrical range about the period, since the period is a more basic measure. Frequency, if I were to use it, would have to be derived from the period. I could find no theoretical grounds for preferring frequency.

9.2.1 Null hypothesis (a) about entrainment: subject period in the experimental condition versus stimulus period.

The relationship between the stimulus period and the subject's preferred period should be <u>different</u> from a perfect integer relationship, except by <u>chance</u>.

Two concepts, <u>not entrained</u> (with respect to difference between periods from a perfect integer relationship) and <u>chance</u>, require numerical formulation. The control trend of the subject's period is crucial to the question of <u>chance</u> in particular.

The numerical definition of <u>not entrained</u> is important, but to some extent arbitrary. Smith et al. (1986) imply that for the stimulus and subject periods, only ratios differing by more than ±25%, constitute behavior that is beyond the limits of normal variability for entrained behavior. Periods related as 1:1.2 would be treated as entrained, under Smith et al.'s definition. This range is, in my opinion, too liberal to be admissible. Two data sets whose periods differ by 25% do not have the appearance of being influenced, one by the other, or by a common drive. I shall restrict the label <u>entrained</u> to cases where the subject and stimulus periods differ by less than ±10%, casting as <u>not entrained</u> the remainder of the field. This way, it is quite unlikely that entrainment should be imputed to occur when in fact it does not.

There is a point of potential confusion: the limits within which entrainment should arise. I have suggested (section **9.1.6**) that entrainment should ensue when the stimulus frequency is within ±15% of the subject's preferred frequency (or of one of its multiples). Clearly, it would not be possible to judge whether entrainment is or isn't occurring when the two periods differ by 15%, if the difference between periods that we permit in the definition of entrainment is greater than a 15% difference between the stimulus and subject periods. The difference between subject and stimulus periods that can be attributed to normal variability in entrained periods must be less than the difference in periods at the limits within which entrainment is likely to arise. So a 25% difference in periods (as in Smith et al., 1986) would be too generous an allowance for variability, given the range within which I expect entrainment (15% about the preferred frequency). A difference between periods of less than 10% seems suitable.

Defining the chance of the occurrence of a particular trend in the experimental period relative to an standard control trend is not possible in numerical terms, because the shape of the control condition cannot be restricted on theoretical grounds (see section **9.1.7**).

The most sensible way of coping with the possibility of these curvilinear control trends is to abandon the traditional methods of looking at average counts or values based on single points, and instead to consider a succession of points.

The event of interest here is the occurrence of ratios of the subject to the stimulus periods differing from unity by less than 10%. (The ratios of 1:1 and 1:1.1 differ by 0.1 (1.1 - 1), and so by 10%.) By chance, two samples in succession might produce data within the limits (10% difference in mean period) that I allow for possible variability in entrained data, but three samples in succession should not do so, unless entrainment truly is occurring. (It is possible theoretically, but the curvilinearity observed in pilot work control conditions was usually shallowly curvilinear, not deeply so. See Figure **9.10** and accompanying discussion below.) It was decided to check subjects' control data to verify that they did not produce curvilinear control data so sharply curved as to refute this assumption.

The three samples in succession that should show entrainment are those taken when the stimulus and first (control or experimental) subject periods differ by less than 15%, that is, the samples taken at the times 3, 4 and 5 in Figures **9.7** and **9.8**, representing stimulus versus initial subject period differences of -10%, 0% and 10%. The maximum absolute difference between subject and stimulus periods that we should see over these three samples if entrainment is truly occurring is 20% (absolute value of -10%, plus 0, plus 10%), based on Figure **9.9**. This is shown by the ratios for the limiting linear control trend c' in Table **9.3**.

Figure **9.9** represents the circumstances in which a stimulus whose period lengthens is required. Only control conditions showing a downward (shortening) trend will require a stimulus that rises (whose

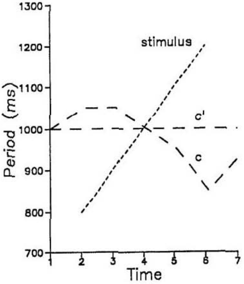

Figure 9.9. An illustration of the null hypothesis: stimulus versus subject period. c and c' are two possible trends for the subject period in the control (or experimental) condition.

period lengthens). Thus horizontal c' is an example of a limiting control trend. Curve c provides an example of the maximum range that is expected. In pilot work, the range of the subject's period in the control condition usually did not exceed ±200 ms of the initial preferred period.

In Figure 9.9, the stimulus and subject periods approach each other closely only where they cross. If the subject and stimulus movements are sampled a total of five times (when the stimulus period differs from the initial subject period by -20%, -10%, 0%, 10% and 20%: times 2, 3, 4, 5 and 6, respectively, on the graph), then in only one of five cases should we expect, based on the control trend, to have a ratio of subject to stimulus period equal to unity. The actual ratios that would be obtained from this data are given in Table 9.3.

Table 9.3 Trends confirming the null hypothesis. Ratios for the data shown in Figure 9.9.

Time	Stimulus Period	c Period	c' Period	Stimulus :c Ratio	Stimulus :c' Ratio
1	-	1000	1000	-	-
2	800	1050	1000	0.76:1	0.8:1
3	900	1050	1000	0.86:1	0.9:1
4	1000	1000	1000	1:1	1:1
5	1100	950	1000	1.16:1	1.1:1
6	1200	850	1000	1.4:1	1.2:1
7	-	925	1000	-	-

The ratios of 1.1:1 and 0.9:1 for samples at times 3 and 5 mean that there is in each case a 10% difference between subject and stimulus period. At time 4 there is no difference between the periods, for the ratio

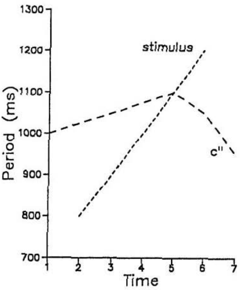

Figure 9.10. The curvilinear control trend (c'').

is 1:1. Summing the differences over the 3 points, we obtain 20%. Note that a control trend that has the shape actually expected (based on pilot work), namely c in Figure **9.9**, will yield a total greater than 20% if the the null hypothesis is accepted. For curve c, the only sample that provides a ratio that connotes entrainment is that taken at time 4. The other four ratios are different from unity from more than 0.1, which results in a greater difference than 20% between subject and stimulus period over the three middle samples.

If the null hypothesis is to be accepted, the three experimental samples obtained at times when the stimulus period is set to differ from the first sample of the subject period by 10% (2 samples) or not at all (1 sample) should yield ratios between the subject and stimulus period that differ from unity by less than 20% in total. If the difference in the ratios is less than 20% over the three points, then I shall have good grounds for claiming that entrainment occurs (see Enright, 1981). This formulation requires that curvilinear control condition trends be checked for the shape and steepness of slope (see sections **11.1.1** and **11.1.2**). Particularly, control trends must be checked to verify that they do not assume the form

Table 9.4. The ratios in the data shown in Figure 9.10.

Time	Stimulus	c''	Ratio
1	-	1000	-
2	800	1025	0.78 : 1
3	900	1050	0.86 : 1
4	1000	1075	0.93 : 1
5	1100	1100	1 : 1
6	1200	1050	1.14 : 1
7	-	950	-

shown in Figure **9.10**, which would vitiate the null hypothesis as presented here. In Figure **9.10**, more than one sample of the two periods, those at times 4 and 5, will yield a ratio that meets the entrainment criteria of less than 10% difference, as Table **9.4** shows.

9.2.2 Null hypothesis (b) about entrainment: subject period in the experimental condition versus stimulus period.

A second possibility that must be considered is that entrainment might occur over three points other than the central three. This occurred in pilot work, and so should be investigated. As argued above, it will be important to investigate a sequence of data, so three samples in succession again will serve. To be acceptable, the difference from a perfect integer ratio of periods must be less than 10%. If any three samples in succession should each show a difference in subject and stimulus periods that is less than 10%, then this would also seem to be reasonable grounds for claiming that entrainment is occurring. There are no cases where this condition is met in the null hypothesis data shown in Tables **9.3** and **9.4**.

As a null hypothesis, then, for any three samples in succession of the five experimental data, the difference between the subject and stimulus periods in each sample should be 10% or greater. The sequence of three ratios with the lowest values will represent each subject in each condition. For both null hypotheses outlined above, a simple count of the number of subjects per condition whose data refute the null hypothesis will be conducted. No subjects should show evidence of entrainment by accident, for I have defined entrainment narrowly, so that by accident, it should not arise.

In this, I heed the admonitions of Enright (1981). He argues that hypotheses about entrainment are most appropriately couched as logical arguments against the arising of entrainment at all. His arguments rely upon entrainment taking a very specific predictable form that would seem, intuitively, very unlikely to arise by chance. If the expected behavior in the experimental condition can be clearly defined, then the difficulty of defining an average expected behavior in a control condition is not problematic for conclusions based on logic. There is no point in defining the expected behavior in the control condition for the experiments here on any basis other than pilot work, which has simply shown that excursions of more than 200 ms from the initial period are unlikely.

Obviously, the method of calculating ratios will be extremely important to the analysis. This is described in Appendix **3** in detail.

9.2.3 Null hypothesis about stimulus effect: congruence of direction test.

If we were to accept the null hypothesis, the trend of the period in the control condition and that in the subject's experimental data should be the same.

The pattern of the length of the period, that is, lenthening or shortening, is the matter of interest. Pilot work showed that subjects' initial preferred periods could vary considerably across days, by as much as 200 ms. However, subjects did tend to repeat a pattern. For example, a subject who started moving at a fast rate (short period) and then slowed over several minutes tended to repeat this behavior. The trend of the subject's period tends to translate to higher or lower starting values across days. The subject cannot undergo the experimental and control conditions simultaneously, and so some difference in the control and experimental data from each subject is likely.

The direction of change of period will be used as the way of quantifying the term same. If the control and experimental trends assume the same shape, then the same pattern of lengthening (positive slope or direction) and shortening (negative slope or direction) of the period should characterize both the experimental and control data. Looking at direction of change in period at once eliminates the need to consider the translation in the trend across sessions, and allows for the occurrence of curvilinear trends. I expected the number of positive and negative changes in the period to be the same in the control and experimental conditions. Figure **9.11** illustrates this formulation graphically.Let us suppose that 7 samples of the subject's movement are taken at the regular intervals. At the end of the first interval (points (a) and (a')) and at the

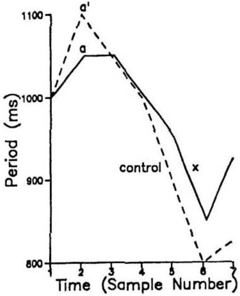

Figure 9.11. Comparing control and experimental data that confirm the null hypothesis. x: experimental data. (a): end of first interval (time of second sample) of experimental data. (a'): end of first interval of control data.

end of all subsequent intervals, it is possible to say whether the period has lengthened or shortened over the interval. In Figure **9.11** it has lengthened before (a), and also before (a').

To accept the null hypothesis, intervals in the two data sets should show the same overall direction of period change, as is indeed the case here. Each subject can be given a score for the number of intervals showing the same direction of change as the overall trend in the control condition, out of the total possible, and these scores may be submitted to statistical analysis.

The overall trend of the control condition is downward in Figure **9.11**, since the period at the 7th sample is shorter than that at the 1st sample. Both the control and experimental data shown in Figure **9.11** would receive a score of 4 out of 6, for the 4 intervals showing an decrease in period out of a total of 6 intervals. The difference between the scores, subtracting the score for the experimental data from the score for the control data, is 0. This indicates congruence of trend between the control and experimental data. This test is referred to as the congruence of direction test. It tests the extent to which the direction of the experimental data is congruent with that of the control data. Under the null hypothesis, there should be no difference between a subject's score for the control condition and that for the experimental condition. If the average difference in scores is statistically different from zero, then there will be statistical grounds for proposing that the rhythmic stimulus has produced an effect. A trend in period which is unlike that of the control will be more like that of the stimulus period, for the stimulus period will be set to take the opposite direction to that of the control trend.

It seemed reasonable to presume a normal distribution for the scores, and so repeated measures regression and t tests could be carried out on these data.

9.2.4 Consideration of relative phase

A priori, relative phase values from 0 to 99% should occur equally often in the entrained data. However, there is a wealth of empirical findings showing a disproportionate occurence of relative phase values of 0, 25, 50 and 75% in entrainment experiments.

The best way of investigating relative phase is by inspecting histograms of relative phase values. Most statistical methods cannot be used because they presume independence of samples. Here, it is to be expected that some subjects should entrain more often than others, or over a greater range of periods. Thus, subjects will probably be unequally represented in the entrained data from which relative phase will be calculated. Sampling cannot be said to be independent.

Nonetheless, in the histograms we should be able to see which values of relative phase are most common. A relative phase value might vary naturally to some extent. This may be inferred from Ehrlich's (1958) study of entrainment, in which subjects were instructed to entrain to a series of stimuli whose period increased or decreased. Based on his results, I calculate the relative phase of the subject to the stimulus period to vary naturally by approximately 5% of the stimulus period. Here, then

I shall consider relative phase values, for example 0%, ±5.

The relative phase values that so commonly surface in the empirical literature, 0%, 25%, 50% and 75%, might be expected to occur 40% of the time just by chance (relative phase values of 0% ±5, 25% ±5, 50% ±5, and 75% ±5). If the relative phase values (±5) of 0%, 25%, 50%, and 75% characterize 70% or more of the entrained data, then I would consider my results to concur with previous findings that show entrainment to occur.

It has been demonstrated (section **9.1.2**) that entrainment is a prerequisite to considering relative phase. Thus, the investigation will follow steps. The first is to establish that entrainment arises, and the second, to examine the particular form that it takes, that is, to see which values of relative phase tend to arise.

9.2.5 Remarks about the null hypotheses

It should be clear from the above that inferential statistical treatments cannot be applied to much of the data. First, my interest is not in individual, independent samples that may produce average values. The average values are not important; only the trend can be said to have meaning. Even with summation over a succession of samples, difficulties arise, due mainly to the multitude of shapes that the control condition data may take. Summing over a curvilinear trend also produces meaningless averages. Summing across subjects is problematic, for some subjects may entrain at 2:1 period ratios, and others at 1:3. Average values taken there would obfuscate the pattern.

The counting measures that I have proposed will not unveil the richness of the data; much of interest will be ignored by these tests. Therefore it seemed wise also to carry out investigations that would not necessarily lead to statistical tests, but would nonetheless enlighten. The ideal method of analysis here is to submit the data from subjects in each experiment to individual analysis. This will be done.

9.3 Hypotheses about Instruction, Task and Stimulus Type (Hypotheses 4, 5 and 6)

9.3.1 Hypothesis 4: instruction

It became clear in Chapter 8 that subjects should not be instructed to entrain. The implications of entrainment for motor organization are only strong if entrainment arises spontaneously and when it would be possible to organize other behavior instead. Accordingly, the instructions to subjects were to perform movements such that they were comfortable. No instructions were given about the regularity or lack of regularity of movement, or about any movement rate. It was stressed only that the subject's movement or repetition should always be comfortable. Also, subjects were not informed that the period of the imposed rhythm would change.

9.3.2 Hypothesis 5: punctate versus continuous stimulus

In Chapter **8**, I asked whether a sequence of regular, well-defined punctate events might drive the subject's period of movement more forcefully than would a sequence of regular, gradual changes in a continuous stimulus. We might see a longer-lasting adoption of the stimulus period, or entrainment more directly in or out of phase, or a larger change in movement rate.

I selected different types of kinesthetic rhythm to test. Accordingly, a rhythm of punctate taps on the skin at regular intervals (the solenoid rhythm) and a rhythm of continuous brushing backwards and forwards on the skin of the forearm (the brush rhythm) was used. The brush changed its direction of brushing at regular intervals. To conclude, I expected to see more evidence of entrainment from the solenoid treatment than I did from the brush. What counts as evidence for entrainment has been defined above (section **9.2**). The solenoid treatment should produce more perfect or near perfect integer ratios of subject to stimulus period and yield a larger difference in scores between experimental and control data for the congruence of direction test, in comparison to the brush treatment. Relative phase in the two conditions can be investigated by inspecting histograms.

9.3.3 Hypothesis 6: stimuli that elicit afference from one as opposed to multiple sources

In Chapter **8** I proposed that a stimulus that elicits afferent information from numerous sources should more forcefully drive the rhythm of a movement, compared to a stimulus that produces afference from one source.

Two types of stimulus were chosen to test this hypothesis. A light brushing back and forth on the skin should elicit afference from only one source, the skin (the brush condition). Externally imposed movements of the arm, on the other hand, should produce afferent excitation from a variety of kinesthetic sources (the arm condition). The afference arising regularly here would be rich: cutaneous afference due to skin stretch at the elbow, spindle afference due to muscular stretch in the biceps and triceps, excitation of joint receptors, and afference from the tendon organs due to stretch of the tendons. The richer barrage of information from the arm, compared to that from the brush, should more powerfully influence the brain. I expected to receive more evidence of entrainment from the arm treatment than from the brush. Data from the imposed arm movement experiment should show more evidence of integer ratios of subject to stimulus period, and larger positive scores on the congruence of direction test, compared to data from the brush experiment.

It is important that the brush and arm treatments be similar in certain respects, specifically, they should both involve continuous stimulation. The latter requirement is not in doubt for the brush, but the arm treatment requires a few words of clarification.

I propose to fix the subject's upper arm in one position, and alternately to abduct and adduct the subject's forearm about the elbow in a horizontal plane (see section **10.2.5**). The kinesthetic stimulation that would arise from these cyclic arm movements is probably continuous over each half cycle of movement for half of the musculature and skin. To be specific, the stretch of skin, of opposing muscles and tendons, which gives rise to afference, occurs only over one half of the cycle of movement. For example, when the arm is flexed about the elbow, the triceps is stretched, and the skin at the inside of the joint is slack. When the arm is extended, the biceps is stretched, and the skin at the inside of the joint is taut. Thus, overall, stimulation is continuous, even if particular muscle spindles are silent for half of each cycle of movement.

9.3.4 Finger movement versus speech movement

The thesis is that speech and finger movement should be similarly organized. Thus, the results from the experiments that involved limb movement will be compared to those that involved speech movements. Under the alternative hypothesis, the congruence of direction tests described in section **9.2.3** should yield similar effects for the finger and speech. The null hypothesis is that the effects should differ. It would not be acceptable statistical practice to entertain a null hypothesis of difference here. Thus, the discussion of this topic with respect to the data will be founded on logical, rather than statistical grounds.

9.4 Task Function, Form and Measurement

The thesis is that organizing speech and other body movements follows similar principles. It then makes sense to consider the type of speech and body movements upon which this analogy rests, as far as the experiments are concerned. The functions of the two tasks from the point of view of the subject should be comparable, and the aspects that are measured by the experimenter should also be comparable for the hypotheses to be fully legitimate.

The common experimental tasks in the field of entrainment study are voluntary continuous oscillation of a limb or segment, usually the index finger (relevant for hypothesis 2), and repetition of a monosyllable (relevant for hypothesis 3). First I consider finger movements and then monosyllable repetition.

9.4.1 The finger movement task

It was important to reduce the amount of afferent information arising from the subject's movement that might be used to formulate a kinesthetic rhythm. For this reason, finger swinging was used rather than tapping (see arguments in section **8.3.1**).

Continuous finger movement up and down in a vertical plane can furnish a straightforward example of oscillation, like that pictured in Figure **8.1**, and should be most economically organized using oscillatory processes.

9.4.2 The monosyllable repetition task

Speech has been explored in experiments on entrainment (eg. Kelso et al., 1983; Smith et al., 1986), always in the form of monosyllable repetition. This task is also of interest here because subjects should retain the speed and complexity of speech movements shown in normal communicative speech. At the same time, their rhythm of speaking should not be influenced by linguistic factors, for example, by the use of stress (accent) on words to convey their importance in a message, or alternation of stress between stressed and unstressed syllables.

Monosyllable repetition should be a more complex task than continuous finger movement. Movements must be made by more segments and organs, estimated to number at least 70 (Gracco & Abbs, 1986), and including at least the mandible, tongue and the cartilages attached to the vocal cords.

One might ask, why not make subjects move the speech articulators without requiring speechlike behavior ? When people raise and lower the jaw without speaking, the movements describe an oscillation similar to a sine wave (Ostry, Cooke & Munhall, 1987), as is also found when people speak (Folkins & Abbs, 1975). However, this type of request does not necessarily elicit fast coordinated movements of many articulators all at once, which is what makes organizing speech movements such a demanding and interesting proposition, aside from the question of planning the linguistic aspects of speech. With speech, one can be certain that numerous articulators are moving simultaneously in coordinated fashion.

9.4.3 Comparability of speech and finger tasks

The tasks of finger movement and monosyllable repetition used here are comparable in that they do not serve any usual function in everyday life, and they generally yield approximately isochronous rhythms, even in isolation (eg. Kelso et al., 1981; Fowler, 1983; Kelso et al., 1983; Smith et al., 1986; Scholz & Kelso, 1989).

Past work suggests that the generally preferred rate of voluntary rhythmic movement should be in general about 1 act per 0.5 sec, with a range in period (across people) of 0.2 sec to 2.0 sec, for both speech and finger movements (based on data from Smith et al., 1986). The effects of a kinesthetic rhythm on the rates of monosyllable repetition and finger movement should be directly comparable.

Restriction to the simple rhythm of a succession of monosyllables sharply limits the scope of any findings. It offers no ground for specific inferences about the way purposeful, fluent natural speech is organized, although it may suggest basic principles that deserve future consideration in discussion of fluent speech.

9.4.4 Measurement

There is one important theoretical question about measurement that needs to be addressed. I intend to measure similar aspects of the finger and speech movement tasks. It is legitimate to wonder how this can be done, if for finger movement, the moment of attaining a particular finger position (the bottom of the movement cycle) is recorded, while for the speech task, sound is recorded. Why is the type of measurement not uniformly applied, and how do these two methods produce results that can be compared ?

The main reason that speech movements are usually not measured in the same fashion as body movements (eg. Kelso et al., 1981; Kelso et al., 1983; Smith et al., 1986) is the relative inaccessibility of the speech articulators, although this is rarely admitted. Only the mandible is easily accessible for measurement. Ostry et al. (1987) observed that gestures of the mandible were similar in speech and non-speech movements, but evidence of this kind is rare. It is particularly difficult to observe vocal cord movement.

The measurement devices that have been used to measure tongue movement are either potentially harmful to the subject (eg. cinefluorography, Tye et al., 1983) or record a limited range of movement (eg. ultrasound shows the height of only the back of the tongue, Ostry, Keller & Parush, 1983; Ostry et al., 1987). Both devices presume relatively stable head posture from the subjects, and for that reason are not suitable to entrainment experiments, where other body parts move simultaneously with the speech organs, and head movements occur naturally.

Most researchers have opted to record speech, on the tacit assumption that important measurable aspects of the speech arise from particular movements, or phases of movement of the speech articulators (eg. Kelso & Tuller, 1983; Kelso et al., 1983; Smith et al., 1986). This is a largely justifiable assumption in the normal case. Forcing air through a certain vocal tract configuration will result in a particular pattern of amplified frequencies that correspond to particular speech sounds, like [u] or [bo] (see **List of Abbreviations**).

A particular vocal tract configuration is achieved by moving the speech articulators appropriately relative to each other. For example, to produce the syllable [bu], the mandible rises and the lips close. The lips then abruptly open, releasing the air pressure that has built up behind them, and the vocal cords begin to vibrate, producing the plosive [b] sound. While the lips are opening, the back of the tongue rises toward the soft palate, and the lips are kept forward and rounded. As long as this posture is maintained and sufficient air flows through the oral cavity, [u] will continue to sound. From the speech sound in the types of monosyllables used here one can presume the relative postures of the speech articulators to a considerable extent.

Many workers look at the integrated speech waveform or the smoothed and rectified acoustic signal (eg. Kelso et al., 1983; Smith et al., 1986). Maximum acoustic energy (a derivative of amplitude) of the vowel has commonly been the measure used in studies of timing and rhythm in simple speech as well (Morton, Marcus & Frankish, 1976; Fowler, 1983). I use maximum smoothed and rectified intensity, a derivative of amplitude.

The time of maximum displacement of the finger and the time of maximum amplitude of the vowel are the events of interest here. The maximum amplitude of the vowel can be taken to stand for the adoption of a relatively consistent and stable tongue posture that lasts between 80 and 250 ms, as the tongue articulates the stressed vowel. The maximum amplitude of vowel sound serves as an approximate correlate of the shape and position of the tongue in the mouth. In the example above, the back of the tongue should be high when the sound [u] is at its loudest. Provided that no unusual objects or perturbations are introduced into the subject's mouth during speech, the measurement of sound and presumption of corresponding movement and/or position should be valid.

Thus, just as the maximum displacement of the finger can be considered to be a cyclic event, so the maximum amplitude of the vowel can indicate the adoption of a stable posture by the tongue, and should also be a cyclic marker.

In this study, the time at which the finger reached the bottom of its swing was recorded. Informal observation of people repeating a monosyllable while swinging the finger showed that speech tended to coincide with the bottom of the swing. Kelso et al. (1983) present evidence of subjects alternately choosing the top and bottom of the swing within a sequence as the basis for synchronization, and so the decision is to some extent arbitrary.

CHAPTER 10

ENTRAINMENT EXPERIMENTS: METHODS

The aim of this chapter is to describe the methods of experimentation and data analysis. Before proceeding to the description of the methodology, let us review the basic design of the experiments.

There were two experimental tasks, finger movement and monosyllable repetition, and three types of rhythmic kinesthetic stimuli. Subjects performed one type of task while being exposed to one type of kinesthetic stimulus. The form of the experimental trials was: the subject performed the task alone. Then the stimulus was introduced. Its period changed gradually and then it stopped. The subject continued to perform the task for a short time. Each subject also performed the task when not exposed to an experimental stimulus (the control condition).

Now that the theoretical aspects of the experiments have been discussed, I shall introduce practical details. While the essential points about data analysis are presented at the end of the methods section here, Appendices **2** and **3** contain further useful explanatory discussion.

10.1 Subjects

Fifteen subjects, 9 male and 6 female university undergraduates, aged 18 to 28 participated in 6 experiments. One of these subjects also participated in the experiments described in chapters 3, 5 and 6. All subjects were naive to the hypotheses that underlay the experiments and were paid for their work.

The main criteria for choosing subjects were: a) that the person not have extensive musical training or be a professional musician, b) that the person find the experimental treatments acceptable, c) that the person be a fluent speaker of English, and d) that the person follow the experimenter's instructions.

Twenty people underwent at least one experimental treatment. Five were rejected as potential subjects on one or more of the above four grounds. The remaining 15 completed all 6 experiments and 2 control conditions described in this chapter.

10.2 Materials

In all experiments and the control conditions a cassette tape player played white noise to the subject's ears at about 80dB through padded headphones. The noise prevented the subject from hearing her own voice or the operation of experimental equipment.

10.2.1 The speech experiment materials

A set of syllables chosen by the experimenter served in the syllable repetition task. These consonant-vowel-consonant (CVC) syllables shared the following properties:

1. They began with a voiced stop consonant [b], [d], or [g] (see **List of Abbreviations.**)
2. Their vowel came from a subset of English vowels: [ɔ], [ɪ], [ɛ], [æ], or [ʌ].
3. They ended with a nasal consonant whose place of articulation differed from that of the initial stop consonant: [m], or [n].

The following properties inhered in this subset. They had a compact, well-defined onset that was picked up cleanly by the recording equipment. The main concentration of energy lay in the vowel. The final nasal finished the syllable smoothly. The syllables could not be run into one another without an audible break, even by the fastest speakers, and the vowels resisted disyllabification well.

In the speech experiments a microphone with cardioid response was suspended by a cloth collar around the subject's neck so that it hung about 130 mm from the subject's lips. The output of the microphone was recorded in one audio channel of a video-cassette recorder.

10.2.2 The finger experiment materials

A finger board with a padded elbow rest, wrist support and finger rest supported the subject's left forearm in the finger experiments (see Figure **10.1**). The subject's moving finger, encased in a black corduroy finger glove, passed between an infra-red light source and an infra-red light detector that were mounted on the board (L in the figure).

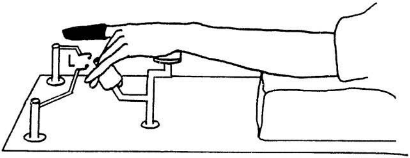

Figure 10.1 Equipment for the finger movement experiments. L: light detector system.

10.2.3 The solenoid experiment materials

The subject's right forearm lay in a cloth and foam-lined plaster cast. It was fixed in the semi-prone position by a padded stop at each side of the wrist (see Figure **10.2**). This prevented movement of the right arm relative to the terminal disk of the solenoid that would contact the arm.

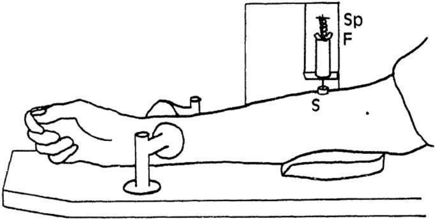

Figure 10.2 The equipment for the solenoid experiments. S: terminal disk of solenoid. Sp: spring. F: foam rubber. The cloth that covered the cast is not shown, for ease of exposition.

The 12 V DC push solenoid was mounted vertically on laboratory jacks on an optical bench that was screwed to a table that was completely isolated from the subject. The solenoid could be raised or lowered into position, so that its terminal delrin disk (10 mm in diameter), S in Figure **10.2**, stood 3 mm above the semi-prone surface of the subject's forearm, about 50 mm distal to the inner elbow. In operation the solenoid disk depressed the surface of the subject's arm by approximately 2 mm.

The solenoid rate was controlled by a function generator using an asymmetrical square wave duty cycle. A gating circuit (see Appendix **1**) gated noise to the recording apparatus simultaneously with the function generator triggering the solenoid push downward.

10.2.4 The brush experiment materials.

The subject's right forearm rested in the plaster cast described in section **10.2.3** and was fixed in semi-prone position at the wrist by padded stops. The board supporting the plaster cast was inclined at an angle of about 10° to the horizontal (see Figure **10.3**), so that the superior surface of the semi-prone forearm at the wrist was at approximately the same height relative to the floor as the superior surface of the forearm at the inner elbow. The brush could then brush evenly over the approximately horizontal semi-prone surface of the forearm. A motor with a maximum torque of 0.27 kg-m (24 lb-ins) that operated at variable speed (in box M in Figure **10.3**) was connected to a delrin shaft that moved in a horizontal plane. The stroke of the shaft was set to 100 mm for the brush experiments. A padded, cloth-covered delrin disk 30 mm in

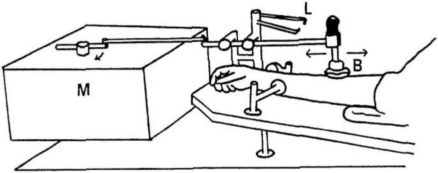

Figure 10.3 The equipment for the brush experiments. Arrows show direction of motion of motor (M) and brush (B). L: light detector system.

diameter was fixed to a delrin rod that slid vertically in a slot at the end of the shaft. This piece of equipment is called <u>the brush</u> (**B** in Figure **10.3**).

When the motor operated, the brush travelled back and forth over 100 mm of the subject's forearm, in contact with the skin from about 70 mm from the wrist to about 50 mm from the inner elbow. Both the motor and the supports for the delrin rings that guided the shaft were isolated from the subject.

A light detector system was fixed to one of the supports for the delrin guiding rings (see Figure **10.3**). The light detector system was set so that the top of the brush rod, which bore a black corduroy collar, broke the infra-red beam twice in each cycle of travel over the forearm.

10.2.5 The arm movement experiment materials

The motor that drove the brush also served to drive the right forearm about the elbow in the arm experiments. The motor shaft was lengthened to produce a 130 mm stroke. The delrin rings that guided the horizontal shaft were mounted on an optical bench that was screwed to the main table surface (see Figure **10.4**). The shaft terminated in a fixture that contained parts of two heavy duty snap closures. The subject's arm was linked at the wrist to the shaft. A padded and stiffened cloth wrist band attached at the subject's wrist to the shaft via the snap closures (see Figure **10.4**). The superior external surface of the wristband attached via two more heavy duty snap closures to closures suspended via wire and a turnbuckle (which is not shown in Figure **10.4**) from a girder above the ceiling. In Figure **10.4**, the superior snap closures

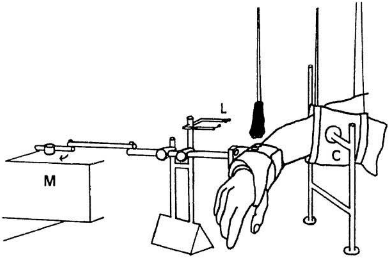

Figure 10.4. The equipment for the arm movement experiments. M: motor box. L: light detector system. C: cloth sling.

on the wristband are depicted as disconnected for ease of portrayal of the apparatus.

This ceiling-wristband-shaft set of connections ensured that the motor moved the arm directly, smoothly, comfortably and safely. If necessary, the subject could break the snap closures to the ceiling wire and the shaft by decidedly adducting the forearm. Stiffening and padding the wristband ensured that the subject could not feel any judder due to the motor if it happened to occur, and would not be adversely affected by the momentum of the freely dangling hand, particularly at the higher motor speeds.

A cloth sling (C in Figure **10.4**) padded with a cloth-covered curved cushion supported the upper arm. It was suspended from a girder above the ceiling by two aircraft cables that passed through turnbuckles (not shown). Padded stops fixed to two upright posts fixed the sling in one position, immobilizing the upper arm, while the forearm was rotated about the elbow by the motor drive at the wrist.

The motor was powerful enough to drive the arm smoothly, provided that the full weight of the arm did not impinge upon it. The motor was chosen so that subjects would be able to arrest it by intentionally resisting the movement of the shaft. This ensured the safety of the subjects, and clearly relieved the anxiety of many of those whose early visits involved an imposed arm movement experiment.

The corollary of this safety feature was that the speeds of the motor could not be precisely predicted from the scale on the motor controller, especially for larger male subjects. The motor had to work harder to displace their heavier and larger forearms, which resulted in slower drive at any point in the scale. The range of experimental rates over which the arm experiments were conducted was increased by 10% or more, as necessary, at either end of the scale to allow for this imprecision. So the rate of arm movement possibly covered up to $\underline{+}40\%$ of the subject's preferred period of repetition or movement. A light source and detector system was used to monitor the arm movements (L in Figure **10.4**).

10.2.6 Recording equipment.

A Sony video cassette recorder was used to collect the data. The microphone was used to record the subject's speech, and when the finger movement task was performed, or any of the stimuli used, the finger or stimulus movement through a light detector system caused noise to be recorded. This was accomplished by gating devices which gated noise from a noise generator into an audio channel of the video-cassette recorder when the light beam was broken as the finger, brush, or arm passed between two light detectors during a portion of their movement cycle.

The sound arising in association with the <u>task</u> was fed into one audio channel of the videocassette recorder, while the noise triggered by the <u>stimulus</u> movement was recorded in the other audio channel. The schematics of the recording and gating devices are provided in Appendix 1.

In the solenoid experiments, the gating devices were connected directly to the function generator that controlled the solenoid, rendering unnecessary the light detector system, but the principle of gating noise still applied, this time directly to the output of the function generator.

The speeds of transmission to recording tape from the light detector system and from the microphone were checked. There was no reliable advantage for either system.

10.3 Instructions and Information Available to Subjects

Subjects were instructed to move their finger (or repeat a syllable) such that they were comfortable. It was stressed that at all times they should feel comfortable. They were told that about a minute after they had begun to move the finger (or repeat the syllable) the stimulus would be presented, and that it would continue for about 5 to 7 minutes before being turned off. They were told to continue at the task until the experimenter tapped on their shoulder, which would be about a minute after the stimulus had stopped.

It was also stressed that they should not tap their toes, or nod their heads, or move any part of their body in accompaniment to the experimental task. Further, they were told to desist from imposing patterns on their repetition of syllables or finger movement, and if they should find that they had innocently slipped into a pattern, to eradicate the pattern immediately.

10.4 Procedure

10.4.1 General procedure: control and experimental conditions

The experimenter told subjects on their first visit of the general procedure for all of the experiments, and what the different experimental treatments were. Then the equipment for that day's experiment was adjusted to fit the subject comfortably and its operation demonstrated. Subjects were given their instructions.

Then subjects put on the headphones. For the experimental conditions, their right arm was strapped into the appropriate arm rest. For the finger movement experiments and the finger movement control condition, the third finger of the left hand was fixed in position on the finger board, and the left elbow placed on the elbow rest. For the speech experiments and speech control condition, the microphone was worn about the neck. Once the subject was comfortable, the noise (at about 80 dB) was turned on through the headphones, and the subject shut her eyes and began the task, either movement of the left index finger or syllable repetition. Subjects kept their eyes shut during the experimental and control conditions, except when drinking from the glass of water provided for their comfort.

10.4.1.1 The control condition.

The control condition results dictated some details of the procedure of the experimental conditions. The trend of the period in the control condition dictated the direction in which the stimulus period would be changed during the experimental condition. If the subject's period was longer in the 7th minute than in the 1st minute, then the subject was considered to have slowed overall over 7 minutes. Otherwise, she was viewed as speeding up overall.

The control conditions were imposed on the subject's third visit, rather than in the first session, because subjects became noticeably more relaxed in the later sessions as they became accustomed to the tasks and familiar with the experimental apparatus. For the control condition to yield reliable data, the subject had to have dismissed any doubts about what the tasks involved before participating in it.

In the control conditions, the subject was not exposed to a rhythmic stimulus, and performed the allotted task until tapped on the shoulder (7 minutes from the start of performance of the task). Their right arm rested on the table or on the arm of the laboratory chair during the experiment.

As an aside, it is worth noting that the term control condition is used throughout to refer to the 7 minute control session described above. The term control portion refers to the initial and final minutes of the experimental condition, during which subjects were not exposed to a rhythmic stimulus.

10.4.1.2 The experimental conditions.

I shall present the procedure for a subject who slows down in the control condition. The procedure for those who sped up in the control required the opposite trend for the stimulus period in the experiment.

It could not be assumed that subjects would always adopt the same starting period of syllable repetition or finger movement, and so control portions were included in all of the experimental conditions. The initial and final minutes of finger movement, which preceded and followed exposure to the sensory stimulus, served as control trials within each experimental session.

The initial stimulus period depended upon the subject's preferred period in this initial minute of any experimental trial and upon the trend of the control condition. If in the control condition, the subject's period had lengthened over the 7 minutes, then the experimenter would plan to set the stimulus period to be long initially, and to become shorter gradually over the experiment. However, the actual starting period for the stimulus could not be set until the subject's period had settled during the initial minute of the experimental condition. After 20 seconds the experimenter measured the subject's preferred period, using the second hand on a wristwatch, and calculated from that what the starting stimulus period should be, knowing that it needed to be 30% longer (shorter) than that of the subject. After a check to make sure that the subject's period was indeed stable, the stimulus period was set for the stimulus controller and the stimulus introduced.

In the experimental conditions, the stimulus was introduced after about 30 seconds. Its period was longer (shorter) than the period of the subject by 30% of the subject's period. The stimulus period shortened (lengthened) over approximately 5 minutes until it was 30% shorter (longer) than the period of the subject had been in the control portion at the beginning of the experiment. The intention was to change the stimulus period so gradually that it would be virtually imperceptible to the subject. The ±30% ensured that the subject would have become accustomed to the presence of the stimulus by the time that the stimulus period had shortened such that it differed from the subject's initial period by 20%, the first point at which the experimental data were sampled.

After 5 minutes the stimulation ceased. Between 30 seconds to 1 minute after termination of the stimulus, the experimenter tapped the subject on the shoulder, and the subject ceased moving the finger (or repeating the syllable). The experiments usually lasted seven minutes, but nine minute experiments were common for subjects who dozed intermittently. Subjects received the same experimental treatment twice in the first two sessions (see below for explanation, section **10.4.3**). The two control conditions for speech and finger movement were imposed during the third visit. In the last four sessions, subjects were exposed to the experimental treatment once. During the first three visits, subjects were given a 5 minute break before the second experimental runthrough (or control condition).

10.4.2 Procedure for particular experiments

For all speech experiments (speech-arm (SA), speech-brush (SB), or speech-solenoid (SS)), the subject's left forearm rested on the table or on the chair arm. A glass of water was placed within easy reach so that the subject could have a drink during the experiment. The microphone was suspended around the subject's neck.

The experimenter assigned a syllable to the subject from the set described in section **10.2** (Materials), counterbalancing syllables across subjects. Subjects repeated the same syllable in their first speech experiment and the speech control condition. In the later speech experiments, subjects were permitted to choose their syllable from the given set. Favorites were /bɪn/, /dɪm/, /gʌn/ and /bæn/.

For all finger experiments (finger-arm (FA), finger-brush (FB), or finger-solenoid (FS)), the finger board supported the subject's left forearm. A cushion supported the elbow, and a padded post supported the wrist. The third digit of the left hand was bent at the proximal interphalangeal joint and attached to a padded inclined post by a cloth collar (See Figure **10.1**). The left index finger moved through an angle of approximately 90° from the vertical, between the infra-red light source and light detector.

In the solenoid experiments, the solenoid disk was positioned 3 mm above the semi-prone surface of the right forearm before the experiment began. The experimenter altered the rate of the solenoid disk to arm contacts by slowly changing the frequency setting on the function generator.

To activate the brush in the brush experiments, the experimenter started the motor. Its speed was changed slowly and after about 5 minutes it was turned off.

In the imposed arm movement experiments, subjects were told to relax their right arm, and especially the right shoulder, and to allow the motor to move the arm freely. They were instructed not to resist the motor, and not to assist its movement either. Subjects could quite easily resist the motor. It was evident from the relatively small standard deviations of the motor rates in the data that resistance, if it occurred at all, was insubstantial.

The supports for the guiding rings were screwed to the main table surface. This resulted in a tiny juddering movement, barely perceptible to touch, of the table surface when the motor shaft changed direction of horizontal motion. To prevent the subject from sensing it, in the finger-arm condition the finger board rested on quilted cloths on the main table surface. In the speech-arm condition, subjects were told not to place their free left arm in direct contact with the main table surface. They were allowed to rest this arm upon a thick, folded cloth, or upon the cushion of the finger board, or upon the arm of the laboratory chair.

10.4.3 Organization of the set of experiments

The order in which the 20 potential subjects underwent the initial two experiments was counterbalanced. The first 2 sessions always comprised one of the speech experiments (SA, SB, SS) and one of the finger experiments (FA, FB, FS), except for one subject. Due to malfunction of equipment in session 2, his first finger experiment occurred in session 3 (and his control condition in session 4).

The control conditions for speech and finger movement were presented in the third session, with their order counterbalanced across subjects, except for the one subject just mentioned. As the trend in the subject's period in the control condition was not known until after the third session, it was necessary to conduct all experiments in the first two sessions twice. Consequently, in the first two sessions, the subject accomplished the experimental task twice, once with the stimulus period lengthening, and once with it shortening.

The subject took a five minute break before repetition of the experiment in the first two sessions. In the third session, a five minute break occurred between the two control conditions. Later sessions required only one run of the experiment. All subjects completed their final four experiments in a different order. Subjects never performed in two different experiments on the same day.

10.4.4 Exceptions to general procedure

Twelve experiments had to be conducted twice, 8 due to procedural error, and 4 due to malfunction of the equipment. One subject was not available for the single re-run of the speech-solenoid experiment required of him for reasons unrelated to the experiment.

All experiments were conducted as described above with the following exceptions. Some subjects spoke or moved their fingers at fast rates that would have required stimuli, particularly arm movements, to be imposed with an unsafely short period. Accordingly, for safety's sake, these experiments were conducted a second time, using a multiple of the subject's preferred period. Four of the experiments that were run twice fell into this class. The second runs of these experiments covered a range of approximately ±30% about double the subject's preferred period.

Several experiments on subjects who moved their finger at rates too slow to permit smooth operation of the motor were conducted the second time over a range that was ±30% of half or a quarter of their preferred period of repetition. For the purposes of comparison, several experiments on subjects whose movement rates fell close to the median preferred period were also run at ±30% of half or double their preferred period.

10.4.5 Calibration of finger movement.

It was important to know when the finger was at the highest or lowest position of its cycle. This was essential for accurate data analysis, since the bottom of the swing was the event that demarcated the period of cycle from the point of view of measurement.

The light detector system was set so that the finger generally spent less time below the light detectors than above them, resulting in less time between two passes through the light beam when the finger went through the bottom of its cycle than when the finger traversed the top of the cycle. However, subjects were able to shift their hand positions during the experiment so as to avoid cramps, and occasionally dozed off, both of which changed the position of their finger relative to the light detector system, so calibration of the system during the experiment was required.

The experimenter calibrated the finger movement through the light detector system every 30 seconds during both control and experimental conditions by connecting the microphone to the audio channel of the videocassette recorder normally used to record stimulus movement and saying "down" when the finger was at the lowest position in its cycle of movement.

The input from the microphone temporarily overrode the stimulus input into the audio channel. The finger movement data were simultaneously recorded in the other channel. So the time of occurrence of the recorded word "down" could be matched against the time of occurrence of gated noise, marking finger movement.

10.5 Data Measurement

The first task here is to establish reliably the time at which a particular event occurs in every cycle. I have supposed that a cycle can be adequately represented by one repeating event, represented by a space-time coordinate. The event is attainment of a certain position after travelling in a given direction, and should not be mistakable for any other measured event.

For the task of analyzing the finger, solenoid, arm, and brush movements, the space-time coordinate chosen was the time at which the maximum excursion occurred (the bottom of the swing for the finger task, the maximum excursion downwards of the solenoid, the point closest to the wrist for the brush treatment, and at the point closest to elbow extension for the arm treatment).

10.5.1 From movement to sound data

The stimulus data and the finger movement data were recorded as pulses of noise. Figure **10.5** displays the transformation from movement to sound. on in Figure **10.5** (upper graph) stands for the noise being gated through to the recording equipment. The upper graph shows the changing position through time of the finger (or the brush or arm). Above the abscissa, the finger is higher than, and below that axis, is lower than its natural resting position. At (c), the finger is at the lowest point in its cycle of movement. (a) and (b) mark the points at which the noise gate is opened and closed, respectively.

The lower graph shows the type of data that are created by the sound gating system and recorded as sound. (a), (b) and (c) match the points of the same name on the upper graph. Each bar stands for the interval in which the finger passed through the light detector system, gating the noise on. (c), the point of interest with respect to judgments

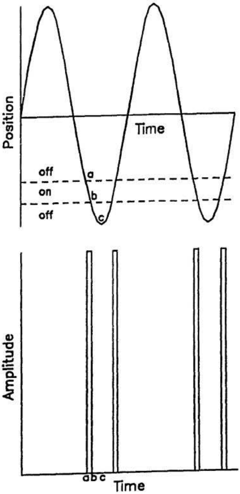

Figure 10.5. **Recording the finger movement or the stimulus movement. on: the noise gate is open and noise is recorded. off: the noise gate is shut. (a): the point at which the finger breaks the light detector beam. (b): the point at which the finger ceases to break the light detector beam. (c): the bottom of the finger movement cycle.**

about entrainment, occurs exactly halfway into the narrower interval between two on bars.

Note that this procedure means in essence setting cut-off marks to distinguish on and off states. For the solenoid data, a single cut-off was applied, as depicted in Figure **8.2**, resulting in one bar for each contact of the solenoid's terminal disk to the subject's arm (at the maximum excursion of the solenoid rod). One bar was considered to be sufficiently reliable for the solenoid data, because the period set by the function generator is very stable, and there were no obvious ways for the subject to alter the solenoid period. However, where the motor or the finger rhythm was being measured, there was potential for variability. For the data to be acceptable, the two bars in each narrowly separated pair had to have the same width, implying that the motor's or the finger movement was symmetrical about the excursion of interest in the cycle. (All 15 subjects' data met this criterion.) In other, similar experiments on finger movement (eg. Kelso et al., 1981; Kelso et al., 1983; Scholz & Kelso, 1989 and 1990), the finger movement was clearly sinusoidal, and appeared to be so here. The light detector system was set to produce as narrow a gap as possible, while still reliably yielding two bars. Commonly, the interval between bars in a narrowly separated pair was 30 to 90 ms for the fastest movement in a data set.

It was assumed that the solenoid bar was symmetrical; at half the interval represented by the single bar, half of the interval of contact with the arm should have elapsed. Speech sound was recorded onto videocassette directly as sound.

10.5.2 Sampling procedure.

It was desirable to obtain samples of behavior in the circumstances that were expected to produce entrainment, and in those that would probably not yield evidence of entrainment. Also, sampling should be regular, to avoid bias. Accordingly, I decided to take five samples of experimental data from the videocassette tapes when the stimulus period was 20% longer than, 10% longer than, the same length as, 10% shorter than, and 20% shorter than the subject's period in the initial control portion of the experimental condition. The initial and final control portions of the experimental condition also yielded one sample each. This sampling procedure has been implied in many of the figures in Chapter **8** and **9**. The control condition data were sampled during the first 30 seconds, and then every 60 seconds thereafter, for a total of 7 samples. The intervals between samples in the control condition data were chosen because they were regular, and were similar to the intervals between samples in the experimental data.

In the experimental data, sampling began when the subject's period had become relatively consistent. The first sample was nearly always taken in the first 30 seconds after the start of the recording. The succeeding samples were taken at intervals of about one minute. Samples were taken at longer or shorter (but non-overlapping) intervals than this when necessary: when subjects dozed off, or sneezed, or took a drink of water, for example. Thus, the intervals between the experimental data samples and those of the control condition are not necessarily the same.

Samples 15 seconds long were taken using a computer which transformed the data and stored it. Some data from subjects whose rates of repetition or finger movement were very slow (S9 and S7) required longer samples to catch even a small number of cycles. Samples 20.5 seconds and 25.5 seconds in length were taken from their data, where necessary.

10.5.3 Digitization

The data were taken from the video-cassette tapes using the video-cassette recorder, an amplifier, and a computer. Computer programs (see Appendix 2) were used to pass 15.4 seconds of sound (that is, one sample) simultaneously from both channels of videocassette tape through an analog-to digital board (a Labmaster board) into an Apco Turbo computer.

The amplitude of the data was digitized using the appropriate computer program from the set: twobar.c (for simultaneous finger movement and light detector data), spl.c (for speech and light detector data), sol.c (for speech and the solenoid data), and solfin.c (for finger and solenoid data). The sampling rates, smoothing procedures, and intensity calculations are described in Appendix 2.

The computer sampling rate was approximately 7200 Hz, and produced amplitude-time data as shown the upper portion of Figure 10.6.

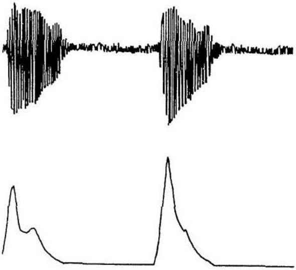

Figure 10.6. Amplitude-time and intensity-time data: The repetition of a monosyllable. Upper trace: amplitude-time. The mean absolute value in every successive scan of 128 data points (18 ms) is plotted. Lower trace: smoothed intensity-time. Total time represented: 2.3 sec.

The data were then smoothed and converted by a squaring procedure to yield a measure of intensity. The important task of these data transformation procedures was to <u>preserve the relative timing of the</u>

amplitude peaks in the speech data, while reducing the number of data points from over 65,500 to 512 for each 15.4 second sample. With respect to the other types of data (finger and stimulus movement), the relative times of the offset and onset of noise needed to be maintained unchanged through any data transformations. It may be seen from Figure **10.6** that the relative timing of the peaks of the speech was faithfully preserved, for the peaks in the intensity data occur at the same time, relative to the beginning of the data and to each other, as do the amplitude-time maxima and minima.

10.5.4 Determining the period

The interval between repetitions of the same events determined the period. So identifying the time of occurrence of the relevant events was the first analytical task. The computer program picked peaks in the smoothed intensity-time data. Figure **10.7** depicts the subsequent peak picking. For speech, the peak fell where the vocal energy was greatest (over a minimum of 60 ms), on the vowel (see Figure **10.7**, upper trace). For the finger movement data, and the brush and arm treatment data, the peak was assigned to the midpoint between every pair of midpoints for two narrowly separated sections where the noise had been gated on (see Fig **10.7**, lower trace). For the solenoid, the peak was assigned to the midpoint of the section where the noise had been gated on. The times at which the peaks occurred was saved in datafiles, and basic descriptive statistics were calculated by computer program <u>freq.c</u> (see Appendix **2**).

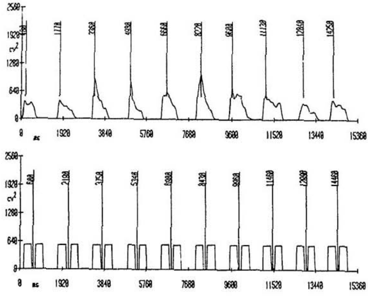

Figure 10.7. Peak picking in intensity-time data. Upper trace: monosyllable repetition. Lower trace: the imposed arm movement data (cv²: centivolts squared).

10.6 Data Analysis

The observation of trends required a numerical scale that is easier to manipulate than are ratios. I devised a scale, called the entrainment index, that had the necessary properties. Trends in data were investigated using the new scale.

The stimulus and subject periods were set in proportion to each other by rules that are given in Appendix 3. The scale is similar to a ratio scale, but it has the advantage of representing multiple and submultiple relationships between two periods in the same way. So for example, a value of 0 on the scale can stand for the perfect integer relationship between any of the following pairs of periods: 1000 and 500 ms, 1000 and 1000 ms, and 1000 and 3000 ms. At the other end of the scale, 50 stands for a relationship that is as far as possible from perfect, implying for example, pairs of periods: 1000 and 1500, and 1000 and 667. The arguments in favor of this scale and supporting examples are furnished in Appendix 3, and the essentials are repeated here.

The index represents the proportional difference from a perfect integer ratio. The procedure is to:

a. divide the longer period by the shorter;

b. discard the number to the left of the decimal, and keep the argument (number to the right of the decimal);

c. multiply the result by 100 (for convenience);

d. if the number is between 51 and 99, subtract 50 from it, and then subtract that result from 50. (If the number is less than 51, do nothing.)

The possible argument (the part of the number to the right of the decimal) values range from 0 to 50. If there is no difference between two periods or they are related as perfect multiples, then the entrainment index value is 0. It arises thus: (a) 1000/1000 = 1.00; (b) loss of the number left of the decimal yields .00; (c) multiplication by 100 yields 0.00. This is the main value that I expect to see if entrainment occurs.

Periods whose ratio is far from perfect produce scale values that are closer to 50. So, for periods 1000 and 1600,

a. 1600/1000 = 1.6

b. Of 1.6, the argument is kept: .6

c. .6 * 100 = 60

d. 50 - (60 - 50) = 40

A few points are worth a mention. First, the argument is the most important part of the quotient that step (a) produces, from my point of view. It shows the departure from a perfect integer ratio, and is the part of the ratio that was represented in the sums featured in the formulation of the null hypothesis. Second, the scale wraps around at the 0 mark, unless correction is made, as in step (d). Step (d) allows the scale to be folded upon itself about 50, which is the value that indicates that the ratio between the two periods differs maximally from a perfect ratio. (A pair of periods such as 1000 and 667 yields an index value of 1.5.)

The salient points about this index follow. Values close to zero indicate entrainment. Based on section **9.2**, entrained will be indicated by index values of less than 10, which means a difference of less than 10% between the subject and the stimulus periods. Values close to 50 suggest that no entrainment is occurring.

The sum of entrainment index values over the middle 3 samples (samples 3, 4, and 5) of each data set was calculated. Also, the lowest entrainment index value from the 3 possible continuous sequences of 3 samples (samples 2 to 6) was recorded.

With respect to phase, the usefulness of the measure of relative phase (or lag) of the subject relative to the stimulus depends upon its consistency. Taking the data that showed entrainment, I checked the variance of the relative phase to construct a data set with stable relative phase before investigating relative phase values.

With respect to the congruence of direction test, the scores for each subject's control and experimental trends were calculated (see section **9.2**) and submitted to repeated measures multiple regression and paired t tests.

CHAPTER 11

ENTRAINMENT EXPERIMENTS: RESULTS AND DISCUSSION

This chapter presents the results of the experiments whose purpose and methods were described in Chapters **8**, **9**, and **10**. I am concerned mainly to show the extent to which entrainment marked the data and whether subjects performed differently at the speech and finger tasks. First, I present the control condition results, then the comparison of experimental and control condition results. Following that the hypotheses about entrainment and the effects of the different stimuli and tasks are considered. Results are discussed as they are presented, due to the large number of hypotheses, the nesting of hypotheses, and the paucity of statistical tests.

11.1 The Control Conditions

The results of the control conditions for the finger and speech tasks are provided in Tables **11.1** and **11.2**, respectively.

11.1.1 The finger movement control data

The column entitled Change in Direction in Table **11.1** gives the number of changes in the direction of the period over the 7 minutes of an experimental session. The subjects changed their period of finger movement over 7 minutes, in absence of any stimulus rhythm. The pattern of the period tended to be markedly curvilinear. A value of 1 or greater in the Changes in Direction column implies a curvilinear pattern of the period across the session. For example, a change of direction value of 1 could mean that the subject initially lengthened her period, and then at some point began to shorten her period and continued to do so for the remainder of the 7 minutes. Thus there would be one change in the direction of period trend, out of a possible 5 changes. (Figure **9.11** shows a control condition that would have a value of 2 for change in the direction of the period.)

The overall trend in the control condition is defined as the overall direction of the period in the control condition. This was determined by subtracting the period from the first sample, taken at time T1, from the period from the last sample, taken at time T7. A positive value meant that the period had lengthened overall, and that the subject's finger movement rate had slowed. The asterisks in Tables **11.1** and **11.2** show the direction of the change in each subject's period. Approximately half the subjects slowed their rate of finger movement over the seven measures (* in the Max + column), and half accelerated. Note that the range of the period is larger than was expected, based on pilot work. The maximum increments and decrements relative to the period in the first

Table 11.1 The finger control condition results.

S	Change in Direction	T1	Max +	Min -	Congruent Intervals
1	2	979	86	294*	5
2	3	1699	659*	-	4
3	2	881	384*	-	5
4	2	1115	-	173*	5
5	5	1990	650*	-	3
6	3	1029	100*	-	4
7	3	2145	690*	-	4
8	3	940	165*	-	3
9	3	3370	-	805*	4
10	2	1004	-	158*	4
11	4	1553	90	50*	2
12	4	1329	-	247*	4
13	1	1480	-	318*	5
14	3	1241	118*	-	4
15	4	1032	212*	-	4

<u>Note</u>: S: Subject Number. Change in Direction: Number of changes of direction in the period. T1: Mean period at the time of the first sample. Max +: largest increment in period relative to period at T1. Min -: largest decrement in period relative to period at T1. In the Min and Max columns, * indicates overall direction of the control trend (if in Max+, * means a lengthening period). Congruent Intervals: Number of changes in period (between successive samples of the period) that took the direction congruent to the overall change in period. Periods are given in ms.

sample, which are shown in the Max + and Min - columns, summed to more than 400 ms for 4 of 15 subjects.

The range of the subject's period is thought to be predictable to some extent from the subject's mean period (Allen, 1975), and the data here reinforce that proposition. Tables **11.1** and **11.2** show that longer periods tend to be associated with a greater range.

Most of the changes in period between two samples in succession did take the same direction as the overall trend. This can be seen from the preponderance of values greater than 3 in the Congruent Intervals column. The largest score possible is 6. The value of 4 for Subject 6 (S6) indicates that the period lengthened between 2 successive samples (an interval) in 4 cases out of 6, so in over half of the data. 4/6 is the mean score across subjects. Further, the relative scarcity of values without an asterisk in the Max + and Min - columns shows that the initial sample at T1 commonly provided the longest or shortest period, implying a trend in a particular direction, rather than variation about a starting value.

The data for the two subjects who did exhibit periods both longer and shorter than the initial period at T1, S1 and S11, were inspected closely. In the case of S11, the trend in period is fairly smooth, and does not pose a problem for the null hypotheses. However, the data from S1 substantiate the problem of defining the null hypothesis that was discussed in Chapter **9**, section **9.2**. Figure **9.10** represents, with some exaggeration, S1's finger movement pattern. Hypothetical entrainment index values were calculated using the periods in S1's control data and the theoretically appropriate stimulus periods, and neither of the null hypotheses outlined in section **9.2** could be rejected.

Generally, subjects displayed a fairly smooth, continuous trend in the period of their finger movement, which took a single, clear overall direction; each subject did not tend to speed up and slow down to a similar extent relative to the starting period. Thus, their data validate the formulation of the null hypotheses in Chapter **9**, section **9.2**. A stimulus rhythm that takes the opposite direction to the overall trend of their period (in the control condition) should provide the circumstance for a suitable test of the hypotheses about kinesthetic influences on entrainment.

11.1.2 The monosyllable repetition control data

Subjects produced similar results when repeating a monosyllable and moving a finger, but there are several minor differences worth pointing out. Table **11.2** is organized in the same way as Table **11.1**. First, the Change in Direction column shows that there were fewer changes in direction of the period of monosyllable repetition, compared to the finger movement control condition. Whereas the mean number of changes in direction in the finger control data was 2.93 per subject of a possible 5, the mean number for speech is 2 per subject. This means that subjects tended either to lengthen or shorten their period of monosyllable repetition more consistently than was the case for finger movement. Nonetheless, the pattern of the period is curvilinear over the control session for all subjects except S8, whose pattern is linear.

Subjects tended to slow their monosyllable repetition over 7 minutes. Thus, the overall trend of the period was an increase in period. By way of evidence, the majority (12/15) of asterisks are found in the Max + column rather than in the Min - column. The first measure of the mean period of syllable repetition (at T1) is similar to that for finger movement, with subjects initially repeating syllables slightly faster on average (1290 ms) than they initially swing their finger (1362 ms). Over all 7 samples, 4/15 subjects produced periods whose range was greater than the 400 ms predicted. This may be deduced from the sum of the Max + and Min - values for each subject.

The subject's period tended, between each pair of successive samples (interval), to take the overall direction of the period. The overall trend was determined as above (section **11.1.1**). The maintenance of trend can be inferred from the Congruent Intervals column of Table **11.2**, where most values are greater than 3 of a possible 6. The mean score per subject is 4.5/6, again reflecting the consistency in the speech data of the trend to lengthen (or shorten) the period over 7 minutes. The difference in these scores in the finger and speech control data was tested statistically using a t test for matched differences. The difference in congruence did not differ statistically for speech and the finger control

Table 11.2 The speech control condition results.

S	Change in Direction	T1	Max +	Min -	Congruent Intervals
1	1	1275	452*	-	5
2	2	1579	332*	-	4
3	3	1255	530*	-	3
4	3	1447	100*	-	4
5	2	1333	422*	-	5
6	2	1160	330*	-	5
7	2	1453	-	258*	5
8	0	1057	314*	-	6
9	2	2652	1323*	-	5
10	2	994	222*	-	5
11	3	1249	128*	-	3
12	2	769	29	91*	4
13	2	1039	119*	24	3
14	2	1006	-	100*	5
15	2	1080	150*	-	5

Note: S: Subject Number. Change in Direction: Number of changes of direction in the period. T1: Mean period at the time of the first sample. Max +: largest increment in period relative to period at T1. Min -: largest decrement in period relative to period at T1. In the Min and Max columns, * indicates overall direction of the control trend (if in Max+, * means a lengthening period). Congruent Intervals: Number of changes (between successive samples of the period) that took the direction congruent to the overall change in period. Periods are given in ms.

data, t (14) = 1.33 (t crit. = 1.76, p = .05, one tail test).

Few subjects varied their period about the starting period (T1), as shown by the general absence of values without asterisks in the Max + and Min - columns. This implies consistency in the pattern of change in this data. The initial period was commonly the longest or shortest, as one would expect for a consistent trend. The pattern of periods for subjects 12 and 13 were examined more closely, as they showed changes in the direction opposite to those of the overall trend, potentially vitiating the null hypotheses proposed in section **9.2**.

S12's data were unproblematic, for the contrary lengthening of the period was minimal. However, S13's speech control data violate the assumptions underlying the null hypothesis proposed in section **9.2**, in that entrainment index values that sum to less than 20 could arise in the 3rd, 4th, and 5th samples, if the subject were to repeat the monosyllable in the presence of the stimulus the same way as she did in its absence. The assumption underlying the second major null hypothesis is not violated: 3 samples in succession would not each produce an entrainment index value of less than 10; only 2 would do so, if the subject performed identically in the experimental and the control conditions.

Otherwise, the subjects' periods described fairly consistent trends across 7 minutes. The periods of finger movement and monosyllable repetition follow similar trends in the absence of an external rhythmic sensory stimulus. The null hypotheses were considered tenable, except for the hypotheses about speech that involved the entrainment index for S13 (section 9.2).

11.2 Performance in the Control vs Experimental Condition

According to the null hypotheses the subject should behave similarly in the presence and absence of an external rhythmic sensory stimulus.

The most basic test of similar behavior in the control and experimental conditions is the test of congruence of direction, as outlined in section 9.2. In the speech and finger control data, the subject's period lengthens or shortens congruously with the overall trend across 4.3 of 6 intervals on average. If, in the experimental data, there are fewer than 4.3 of 6 changes in period that take the same direction as the overall control trend, then it will be reasonable to argue that the stimulus has had an effect. By design, every interval between samples of the stimulus rhythm shows a change in period opposite to that of the subject's overall trend in the control condition. In theory, the stimulus should drive the subject's period in the opposite direction to the overall direction of the control trend.

On average, the subject's period took the overall direction of the control condition in 1.06 fewer intervals in the six experiments than in the control condition: F (17, 71) = 57.0, $p < 0.0001$. (This test used

Table 11.3 Congruence of direction results.

Expt	d	df	s_d	t
FS	1.0	14	4.3	3.41
FA	1.4	14	5.4	3.87
FB	0.7	14	6.3	1.58
SS	1.3	13	6.3	2.85
SA	1.7	14	5.4	4.62
SB	0.3	14	5.6	0.89

Note: Expt: Experiment (FS: Finger-Solenoid; FA: Finger-Arm; FB: Finger-Brush; SS: Speech-Solenoid; SA: Speech-Arm; SB: Speech-Brush) d: mean difference between number of intervals in the control data whose period is congruent with the overall trend and the number of congruent intervals in the experimental data (see text). df: degrees of freedom. s_d: standard deviation of the difference. Critical t(14) = 2.62, $p < 0.01$ (one tail).

repeated measures multiple regression and was performed after the variance due to the subjects' vectors had been removed.) The subject's period lengthened or shortened with the stimulus period. Therefore, the direction of the change in period over each interval between samples became more congruent with the direction of the change in the stimulus period. This result is not sufficient to indicate that entrainment must characterize the data, but is supportive of that hypothesis, and a statistically non-significant finding in this test would have suggested that entrainment was probably not strongly present, if at all.

In each experiment, the subject's period was less frequently congruent with the overall direction of the control session than had been the case in the control condition. The finding does not reach the level of statistical significance in the brush experiments, as Table **11.3** shows. A conservative statistical significance level of $p = 0.01$ has been adopted for these one tail t tests, resulting in critical values of $t(14) = 2.62$, and $t(13) = 2.65$. The mean difference between the numbers of experimental and control intervals in which the mean period was congruent to that of the control trend is given in column d.

11.3. Performance in the Experimental Condition

Section **11.2** indicates the presence of rudimentary signs of entrainment. Now I shall consider the null hypotheses from section **9.2**, first with respect to the finger movement experiments, and then with respect to speech. There was an interaction between the task (speech or finger movement) and the stimulus type (solenoid tap, brush or arm movement) in the entrainment index results, and so the finger and speech results are presented separately.

The measure used in this section, the entrainment index, arises from the ratio of the subject's period to the stimulus period (see Appendix **3**). The pattern of variability of the subjects' periods was checked by inspecting the pattern of the lag within each sample (see Appendix **3**). None of the subjects' data revealed the presence of unequal intervals between successive movements (as in Figure **9.5**), and so the entrainment index (EI) values given here are considered to be valid.

11.3.1 The finger experiments

There is considerable evidence for subjects entraining their movement to the stimulus rhythm. The pertinent entrainment index values for the finger movement experiments are given in Table **11.4**.

The first null hypothesis was that the middle three experimental samples should not yield a total entrainment index value less than 20 (see section **9.2**). The total entrainment value for the middle samples (T3, T4 and T5) is given in Table **11.4** in the columns labelled Mid. The maximum sum possible is 150. The asterisks indicate a refutation of the null hypotheses. The bottom row of the table gives the total number of subjects whose data refuted the null hypothesis. Four of fifteen subjects entrain when exposed to the arm movement treatment and the brush, and 5/15 do so when exposed to the solenoid, as they move their finger up and down.

The second formulation of the null hypothesis, namely, that the subject's movement will not produce 3 entrainment index values less than

Table 11.4 Entrainment index (EI) values for finger data

S	Experiment					
	FS		FB		FA	
	Mid	Best	Mid	Best	Mid	Best
1	45	32	39	39	58	28
2	7*	3*	17*	6*	10*	5*
3	41	41	89	62	5*	5*
4	8*	8*	4*	1*	11*	4*
5	34	32	46	35	25	13$
6	10*	10*	61	52	107	67
7	11*	11*	58	36	76	75
8	38	11*	96	52	63	29
9	65	64	56	37	73	73
10	84	54	112	87	115	77
11	30	20*	97	86	16*	6*
12	60	44	40	22	86	76
13	75	75	33	33	65	59
14	18*	18	14*	7*	37	22
15	65	28	16*	16$	24	22
*	5	6	4	3	4	4

Note. S: Subject number. Experiments: FS: Finger-solenoid; FB: Finger-brush; FA: Finger-arm. Mid: Sum of the entrainment index (EI) values from the middle three samples. Best: Sum of the entrainment index values from the sequence of three samples with the lowest total. *: refutes the null hypothesis. $: one (borderline) EI value of 10 included in the sum.

10 in succession over the five middle samples, is addressed by the data in the columns in Table **11.4** that are labelled Best. These give the lowest sum of the entrainment index values over 3 successive samples from T2 to T6 in the experiment. $ indicates that one borderline entrainment index value of 10 contributed to the sum.

Much the same result as that just mentioned arises here too. Three subjects of fifteen entrain in the finger-brush condition, while 4/15 do so in the arm experiment, and the highest number, 6/15, change their period of finger movement so that it becomes similar to that of the solenoid. The subjects entrained their finger movement to a rhythmic sensory stimulus in approximately one third of the experiments. Entrainment is not mandatory, but is a very prominent type of behavior, given that there was no instruction to entrain. On both Mid and Best measures, the solenoid yielded the strongest evidence of entrainment, and the brush the weakest.

11.3.2 The monsyllable repetition experiments

The two null hypotheses just entertained with respect to finger movement will now be considered with respect to the speech experiments. Table **11.5** presents the relevant data in the format used for Table **11.4**. S5 did not participate in the SS experiment, and so his values are missing.

First, note S13's results. S13 was the only subject whose trend in

Table 11.5 Entrainment index (EI) values for speech data

	Experiment					
	SS		SB		SA	
S	Mid	Best	Mid	Best	Mid	Best
1	53	24	59	24	15*	15*
2	17*	7*	15*	15*	11*	5*
3	96	65	45	31	50	31
4	25	4*	30	11*	17*	17
5	-	-	20$	20!	20$	20*
6	45	22	65	35	42	6*
7	4*	4*	13*	13	3*	3*
8	52	15	45	28	28	14*
9	94	69	54	29	101	76
10	32	23	38	26	25	13*
11	125	113	76	76	15*	15$
12	44	33	62	56	42	26
13	31	20$	47	25	25	25
14	74	44	93	49	19*	19$
15	15*	15	19*	19	13*	9*
*	3	3	3	2	7	8

Note. S: Subject number. Experiments: SS: Speech-solenoid; SA: Speech-arm; SB: Speech-brush. Mid: Sum of EI values from the middle three samples. Best: Sum of EI values from the sequence of three samples with the lowest total. *: refutes the null hypothesis. $: one borderline EI value of 10 included. !: two EI values of 10 included.

the control condition, if repeated in the experiments, could have (wrongly) implied a refutation of the null hypotheses. Her data yielded

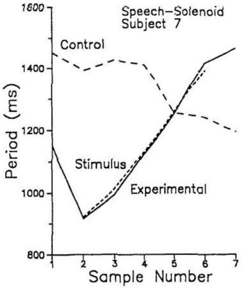

Figure 11.1 An example of entrainment from S7 in the speech-solenoid experiment.

low entrainment index values, as expected based on her control condition data, but none that have been counted in the bottom line totals as refuting the null hypotheses.

The subjects synchronize their monosyllable repetition to some extent with the brush and solenoid movements. Three subjects entrained their syllable repetition to those stimulus rhythms over the middle three samples (T3, T4 and T5). The data from one of these subjects, S7, is displayed in Figure **11.1**. (In fact, S7 entrained his monosyllable repetition to the solenoid rhythm throughout the experiment.) Generally, the arm movement treatment had a more powerful effect, inducing 7/15 subjects to entrain over the middle samples (see Table **11.5**).

Looking at the entrainment index values from any sequence of three samples from the central five (the <u>Best</u> data), one sees similar results. Entrainment in the brush experiment is reduced, with 2/15 subjects entraining. The results for the solenoid treatment are similar, with 3/14 entraining. The imposed arm movement induces 8/15 subjects to entrain, and 2 more produced borderline results. This is clear evidence of a tendency toward entrainment.

Every experiment, featuring either task, yielded some evidence of entrainment, with at least 2/15 subjects synchronizing their movement to that of a stimulus over at least 3 samples (approximately 2 minutes). The cases with asterisks in the <u>Mid</u> columns of Tables **11.4** and **11.5** and <u>still lower</u> EI values in the <u>Best</u> columns (eg. S4 for FB and FS) show that subjects entrained over 4 or 5 of the 5 samples taken when a stimulus was active.

Entrainment arose in every experimental condition, and was exhibited by 12/15 subjects in at least one experiment. This is a powerful result, given that entrainment could not be expected to arise at all under my formulation of the null hypotheses. Clearly, entrainment is an important kind of behavior. Given that there was no instruction to produce the entrainment, and no reason to suppose that it furthered the subjects' goals in any way, it seems likely that the tendency to entrain to sensory stimuli is basic in the organization of finger and speech movements.

The speech task produced more extreme results than the finger movement task. Fewer subjects synchronized their monosyllable repetition (compared to their finger movement rhythm) to the brush and the solenoid rhythms, but more subjects entrained their speech to the arm movement rhythm. This interaction is discussed below (section **11.7**).

11.4 Relative Phase

Having found good evidence of entrainment in the data, it is now possible to investigate relative phase. Here, I give the relative phase as a percentage (see section **8.2.2**). The stability of the entrainment in all data that produced low EI values was verified against the appropriate value in the table of relative phase variances given in Appendix **3**. Those with variances that were large enough to suggest that the relative phase values might be unstable were removed from the relative phase data (see section **9.1.5**). 41.5% of the data were rejected on these grounds, leaving 103

Table 11.6 Fraction relative to total of commonly observed relative phase values in the data with low EI values.

	Experiment					
S	FS	FB	FA	SS	SB	SA
1	0/1	-	-	0/1	0/1	0/1
2	3/4	2/3	1/4	2/2	1/2	0/3
3	-	-	1/4	-	1/1	1/1
4	0/2	1/3	1/2	1/3	2/2	1/2
5	0/1	-	1/2	-	1/1	-
6	2/4	1/1	-	1/1	1/1	1/2
7	-	-	-	3/5	0/2	0/4
8	0/2	-	1/1	0/1	1/1	0/2
10	-	0/1	1/1	-	1/1	0/1
11	0/1	-	0/2	-	-	1/1
12	-	1/1	1/1	-	0/1	-
13	1/1	0/1	-	0/1	-	0/1
14	2/2	1/3	1/2	-	0/1	0/1
15	0/1	0/2	-	1/1	1/1	1/1
Tot	8/19	6/15	8/19	8/15	9/15	4/20

Note. S: Subject number. S9 contributed no data to this analysis. FS: Finger-solenoid. FB: Finger-brush. FA: Finger-arm. SS: Speech-solenoid. SB: Speech-brush. SA: Speech-arm.

cases with very stable low entrainment index values.

A priori, one would expect the relative phase values of 0% (synchrony), 25%, 50% (antiphase), and 75% to occur no more frequently than any other relative phase values. These values, ±5, should not occur in more than 40% of cases, on average. The number of relative phase values that fell about these commonly obtained values (±5) was noted. Each subject contributed one fraction per experiment.

The special values of relative phase that commonly mark entrainment in the literature, 0%, 25%, 50% and 75%, occur no more frequently than other values, on average. Table **11.6** displays the frequency of the values of 0%, 25%, 50%, and 75% of relative phase. In 42% of the samples the relative phase values of 0%, 25%, 50% or 75% (±5) arose, a percentage scarcely different from the 40% value of chance. Even when a subject provided a sequence of samples with low EI values, for example, S2 in all experiments, the chance value is hardly exceeded by much: S2's sum is 9/18; only half his entrained samples show the commonly reported relative phase values.

This is not to say that all phase values are equally well represented in the data. The histogram of the relative phase across all experiments (Figure **11.2**) indicates that the relative phase values are not randomly distributed over the range. There are clusters of common values with a broader base than ±5. Moreover, the clusters are offset in a reliable fashion from the values that the literature reports; they are in advance of these relative phase values by 10%.

The subject's movement tends to anticipate the end of the cycle of stimulus movement slightly, or the half, quarter, or three quarter cycle of

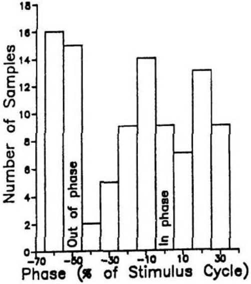

Figure 11.2 The mean phase of the subject movement relative to the stimulus movement, as a percentage. -50 and +50 represent movement that is directly out of phase (-180° and +180°, or the half cycle); -25 and 25 represent the three quarter and quarter cycles, respectively; 0 represents in phase movement (the full cycle). Subjects are unequally represented in these data.

its movement. The major peak occurs at -60%, and includes data that were directly out of phase (the shoulder of the peak, at -50%). The subject tends to be 10% in advance of the halfway point in the stimulus cycle. The next largest peak is at -10%, indicating that the subject tended to say the syllable 10% in advance of the endpoint of the stimulus cycle.

Table 11.7 Most common values of relative phase (%).

	Experiment					
Phase	FS	FB	FA	SS	SB	SA
-50	-50	-	-60	-	-50	-60
-25	-	-20	-	-	-	-
0	-	-	-10	0	-	-10
25	20	20	25	-	30	-

Note. Phase: Phase of subject's movement relative to the stimulus movement. FS: Finger-solenoid; FB: Finger-brush; FA: Finger-arm; SS: Speech-solenoid; SB: Speech-brush; SA: Speech-arm. Every phase value represents at least 3 data.

A peak at 20% also suggests a tendency to speak or complete a movement slightly in advance of the quarter mark of the stimulus cycle.

Every experiment produced a mode at a value in anticipation of, or on, the quarter, three quarter, half or full cycle of the stimulus. Table **11.7** shows the main values of relative phase per experiment. For each type of experiment (FA, SA, etc.) a histogram of phase values was compiled (see Figure **11.3** below for example). If there were 3 or more 15 second samples whose relative phase fell in an interval, then the midpoint of that interval was entered into Table **11.7**. The pertinent intervals are relative phases of 0 ±5, 25 ±5, -50 ±5 (50 ±5), and -25 ±5 (75 ±5). Only two values that indicate the subject lagging the stimulus commonly occurred, both arising in the brush experiments (FB: -20, and SB: 30). All other most frequent values are either in advance of one of the commonly observed relative phase values, or are at one of these phase values.

Table 11.8 Proportion of entrained samples that lead and lag the stimulus.

	Stimulus Change (#S)	Lead	On	Lag	Other	(N)
F	Longer (7)	.59	.06	.29	.06	17
	Shorter (8)	.51	.03	.37	.09	35
S	Longer (3)	.73	0	.07	.13	15
	Shorter (12)	.53	.08	.31	.08	36

Note. Stimulus Change (#S): Direction of the stimulus change over the experiment (longer or shorter period), and the number of subjects for which each direction of stimulus change was applied. Lead: The proportion of entrained samples in which the subject peaks preceded the quarter, half, three-quarter, or full cycle mark of the stimulus movement by 10% of the stimulus cycle or less. On: The proportion of entrained samples in which the subject data peaks occurred exactly at the quarter, half, three-quarter or full cycle mark of the stimulus movement. Lag: The proportion of entrained samples in which the subject peaks lagged behind the quarter, half, three-quarter or full cycle mark for the stimulus movement by 10% of the stimulus cycle or less. (N): total number of entrained samples. F: Finger movement data. S: Speech movement data.

Why the offsets should be so regularly anticipatory is not clear and is discussed in the conclusions (section **11.11**), but their patterning does strongly suggest entrainment-like behavior. One could assume that the subject is in effect treating the stimulus as though it is perfectly periodic, which it is not. If this is so, the subjects should constantly adjust their period of movement as that of the stimulus changes. A subject then will commonly anticipate the slowing stimulus slightly, entraining to it by lengthening her period only after the stimulus slows. Subjects for whom the stimulus period lengthened tended to anticipate the stimulus strongly, and those for whom the stimulus period shortened tended to lead the stimulus less strongly, but the effect is slight, in comparison to the strength of the general tendency to lead the stimulus, as Table **11.8** shows. The tendency to lead the stimulus is pronounced and consistent across the finger and speech data and the two directions of stimulus period change. (It is not legitimate to conduct an inferential $\underline{x}^2$ test, due to the unecual contributions by subjects to the proportions in the table. Multiple and unequal representation violates the sampling assumptions.) There is no obvious theoretical reason for the clear tendency to lead the stimulus.

The relative phase data suggest that an entrainment-like process is occurring. The subjects did tend to produce certain values of relative phase that were approximately one quarter or one half cycle (25% or 50% of the stimulus cycle) apart: -60%, -10%, and 20%. Surprisingly, these main values were not on the quarter, three quarter, half and full cycle of the stimulus, but instead fell about 10% of the stimulus cycle in advance of those landmarks.

11.5 The Stimulus Type: Punctate vs Continuous

Now let us consider hypothesis 5: that a punctate stimulus will tend to induce entrainment to a greater extent than will a continuous stimulus. For the finger experiments, Table **11.3** (the congruence of direction table) shows a fairly small difference between the solenoid and brush effects: the solenoid treatment yields slightly more evidence of entrainment than does the brush treatment (on average, 0.3 more intervals in the solenoid data showed the subject's period taking a direction that differed from that of the control condition). In the monosyllable repetition experiment this effect is stronger: 1.0 more intervals in the solenoid experiment showed the subject's period taking a different direction from the control trend, compared to the brush experiment. The predicted effect occurred in both experiments. It is weak when the finger movement is the task $\underline{t}(14) = 0.8$, $\underline{p} > 0.025$, and statistically significant when speech is the task, $\underline{t}(13) = 2.44$, $\underline{p} < 0.025$. (Alpha is split between the simple main effect tests (Pedhazur, 1982).) Thus, a punctate stimulus like a tap on the wrist tends to cause the period of the subject's movement, particularly speech movement, to change to become more like that of the stimulus. A continuous, smooth stimulus, like a brushing rhythm will also produce this effect, but less strongly.

The power of the solenoid as an entrainer when the finger moves is indicated in Table **11.4**. In the finger experiment, the solenoid induced more subjects to entrain over the 3 middle samples (Mid columns) than did the brush, but the difference is small: 5 cases for the solenoid, and 4 for the brush. The difference between the effects of the two types of stimulus is more pronounced in the data which required a sequence of data from 3 intervals, each with an EI value less than 10 (Best columns); in 6 cases, the solenoid induced entrainment, but the brush treatment yielded only 3 cases. This suggests that when the finger is moved in the presence of the solenoid, entrainment is maintained for longer than with the brush, and begins or ends quite commonly outside the middle 3 samples. Thus the range over which the solenoid induces entrainment may be greater than that which applies when the brush is the stimulus.

In the speech experiments, less entrainment arose due to either the solenoid or the brush, compared to the finger experiment. Also, both stimuli produced similar effects, even when the best sequence from 5 samples was investigated (the Best columns of Table **11.5**). However, the rank ordering of the speech and finger results is the same: the brush experiment can be viewed as having produced the least entrainment for both.

The finger experiment produced the stronger result with respect to entrainment, while the speech experiment yielded the stronger result on the congruence of direction test discussed above, which measures the strength of the attraction of the stimulus rhythm for the subject, relative to control condition performance. The two tests measure different aspects of behavior. In the speech data, the subject's period changed to take the direction of the stimulus more <u>often</u> than occurred in the finger experiment. However, the average <u>magnitude</u> of the change in the direction of the stimulus period is greater in the finger experiments. The greater magnitude is what is required to produce low EI values, and can account for the different strength in the two results.

When both the entrainment results (Tables **11.4** and **11.5**) and the congruence of direction results are considered, it is proper to consider the solenoid to be a more potent entrainer than the brush. The brush appears to be the least effective driver on all measures, when either the speech or the finger movement task is used. However, the difference in effect due to using a punctate, rather than a continuous, stimulus is not large. Further experimentation would be needed to confirm the effect.

There might be differences in relative phase if the solenoid is the stronger entrainer. The solenoid and brush show similar numbers of occurrences of the predicted phase values (0%, 25%, 50%, and 75% of the stimulus cycle, ±5): 16/34 (.47) for the solenoid, and 15/30 (.5) for the brush (see Tablel **11.6**). Thus, the solenoid and the brush movements are very similar in terms of the rigidity of their phase relationship with the subject's movement.

11.6 Stimulus type: Sources of Afference

Hypothesis 6 was that afference that arose from a number of sources should more powerfully induce entrainment. The brush and imposed arm movement experimental results speak to this topic. The arm treatment yielded more evidence of entrainment, as predicted. The interpretation is complicated by an interaction between the task type (speech versus finger) and the stimulus type (arm versus brush).

From Table **11.3** it was calculated that in the arm experiments, there was an average increase of 1.6 out of a possible 6 intervals showing the subject's period taking the direction of the stimulus, relative to the control condition. For the brush, the change in direction of the period towards congruence with the trend of the stimulus period occurred in only 0.5 intervals on average. In the finger movement data, the change of 0.73 intervals represents a small effect on the borderline of statistical significance: $\underline{t}(14) = 1.98$, $0.025 < \underline{p} < 0.05$ (one tail test). The difference between the arm and brush treatments is much larger in the speech experiment: 1.33, $\underline{t}(14) = 3.84$, $\underline{p} < 0.005$ (one tail test). Thus, the subject tends to change the direction of his period toward that of the stimulus more often when his arm is being moved externally, compared to the frequency of direction change when the brush is applied.

The entrainment data from Table **11.4** weakly support the observation that the arm treatment yields the more powerful entrainment. When the finger movement task is used, imposed arm movement is slightly better than the brush at inducing entrainment, to judge by the one case advantage for the arm treatment in the Best column (4 for the brush, 5 for the arm). Over the central 3 samples (the Mid columns), there is no advantage for either treatment.

For speech, however, the evidence is clear-cut. Seven cases of entrainment (the Mid columns of Table **11.5**) mark the arm movement data, and there are only 3 in the brush experiments. As above in section **11.5**, the pattern under consideration appears in more exaggerated form in the Best columns. Eight cases of entrainment arose when the arm was moved, and only 2 when the brush was applied.

Both finger and speech experiments show a superiority for the arm treatment, even though the effect is much stronger in the speech movement data than in the finger movement data. Exposure to a rhythm of imposed arm movement yields entrainment more commonly than does exposure to a brush moving on the skin.

Afference that arises from numerous sources then induces more entrainment. The difference between brush and arm effects in the Best columns suggests that with the arm treatment, entrainment may begin earlier and end later, or occur over a larger range of periods, relative to the subject period.

It is interesting that the Best columns in Tables **11.4** and **11.5** show a reduction in the number of entrained cases associated with the brush treatment, relative to the Mid column data. When the brush induces the subject to synchronize, the brush and subject periods tend to be very similar over one or two samples, but not commonly over three. On the other hand, the style of entrainment associated with the arm treatment tends to be longer lasting, with low EI values being maintained over 3 or more samples, as shown by the higher numbers of entrained subjects on the Best measure, compared to the Mid measure. This is a more common outcome than near zero EI values being produced over fewer samples.

It is worth asking whether the pattern of the phase relationship of subject to stimulus movement distinguishes the effect of the arm treatment from that of the brush. The phase relationships of 0%, 25%, 50% and 75% relative to the stimulus cycle marked the arm data less frequently than the brush data: in 0.3 versus 0.5 of the entrained samples, respectively. This is due largely to the anomalously low proportion of the samples from the speech-arm experiment that show these phase values, 0.20 (see Table **11.6**). The anticipation of the stimulus that was mentioned above in section **10.4** is very noticeable here. Thus, the failure of the speech-arm data to show the phase values commonly reported in the literature does not imply a random distribution of phase, but rather a very decided tendency to anticipate, by about 10% of the stimulus period, the half, three quarter, quarter, or full cycle mark of the stimulus, as Figure **11.3** shows. Fully .65 of the phase values fall into the categories -65 to -55 (before half cycle), -35 to -25 (before the three quarter cycle), -15 to -5 (before the full cycle mark at 0), and 15 to 25 (before the quarter cycle). The expected proportion is .40 (see section **11.4**). There is a possible reason for this anticipation (see section **11.11**), and it is

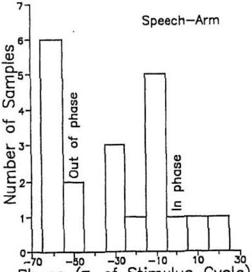

Figure 11.3 **Histogram of the speech-arm relative phase data. The mean phase of the subject relative to the stimulus. -50% and +50% represent movement that is directly out of phase; -25% and 25% represent the three quarter and quarter cycles, respectively; 0% represents in phase movement (the full cycle). Subjects are unequally represented in this data.**

sufficiently important to deserve further investigation.

On the measures mentioned here, the finger and speech tasks are associated with the same kind of effect, although the speech task is reliably associated with a more powerful effect. In the phase data, the speech-arm results, which appear at first glance to betoken weakness, in fact merely imply narrower ranges of the relative phase values common in the other experimental data.

On all measures of entrainment, congruence of direction, and the EI value sequences, the imposed arm movement produces an effect that is at least as powerful as that of the brush, and so there are grounds for concluding that the number of sources of afference that are excited is a factor in determining the strength of entrainment. It is particularly important when a monosyllable repetition task is used.

11.7 Speech vs Finger Task

The null hypothesis was that the speech and finger movement tasks should yield different results. This renders problematic the use of statistical tests that assume a null hypothesis of similarity. So no statistical test for the congruence of direction in the speech data versus the finger data was performed.

The mean congruence of direction values are susceptible to an obvious interpretation, in any case. The number of intervals in which the subject's period changed direction, becoming more similar to that of the stimulus, was virtually the same in the speech and the finger movement data, and the rank order of effects for each stimulus type was the same for both tasks. Thus, for both the finger movement and the speech tasks, imposed arm movement yielded the strongest evidence of entrainment, the solenoid was the next most effective stimulus, and the brush had the least effect. Table **11.3** provides evidence. The mean change per subject toward congruence with the stimulus trend in the monosyllable repetition experiment is 1.1 intervals, while in the finger data it is 1.03 intervals. The difference between these two values, or the difference in effect associated with the task, is 0.07 intervals on average, a miniscule and insignificant advantage for speech.

Next, Tables **11.4** and **11.5** indicate virtually identical proportions of entrained cases across speech and the finger experiments: 13 of 45 experiments for the finger movement task, and 13 of 44 experiments for the monosyllable repetition task. The interactions between task and stimulus in the entrainment results (Tables **10.4** and **10.5**) have been noted in many of the sections above. The solenoid treatment is most effective when finger movement is the task, and imposed arm movements drive the subject's period most strongly when syllable repetition is the task.

It is important to note two points about the entrainment data. First, the brush treatment is least effectual in association with both tasks. Second, the differences in the finger data for the solenoid and arm treatments derived from Table **11.4** may not be important, as they are fairly small. The difference is 1 case out of 15 in the *Mid* data, and 2 cases out of 15 in the *Best* data.

If a trend is to be drawn from all of the data, it should be that of the congruence of direction tests. There, for *both* speech and the finger movement tasks, imposed arm movement is the most potent driver, followed by the solenoid. This trend is repeated in the speech entrainment data shown in Table **11.5**. It is likely that the sum of EI values across the 3 stimulus types is a veridical indicator of the effect of task type for *the speech experiments*. The one anomalous trend is in the entrainment data that arose from the finger-arm movement experiments. There are good grounds for asking whether the imposed arm movement rhythm was deliberately resisted in the finger-arm experiment, yielding fewer cases of entrainment than might have been the case if the imposed rhythm were less salient.

Many subjects stated that the arm rhythm was extremely difficult to ignore when they moved their finger. At least two subjects, S14 and S1 , consciously attempted to resist the rhythm of arm movement when moving their finger (see below, section **11.10**). No other experimental manipulation elicited such comments. Accordingly, I judge the trend shown in the finger-arm experiment entrainment data to be less trustworthy.

The proportions of entrained cases for speech and finger movement, based on the brush and solenoid experimental results, are fairly similar: 0.21 for the speech-solenoid and speech-brush experiments, and 0.3 for the finger-solenoid and finger-brush experiments (see the Mid columns, Tables **11.4** and **11.5**). This is a fairly small difference. At the most, the difference is 0.17 versus 0.3 (the Best columns). On the other hand, the finger-solenoid data revealed a weaker effect than did the speech-solenoid data, according to the congruence of direction results. In sum, the results cannot decide the question of which task, speech or finger movement, is more open to kinesthetic drive. Both appear to be similarly susceptible. It is possible that the finger movement task might produce more cases of entrainment than did the speech task, if subject attitude could be controlled in the finger-arm experiment.

Overall, for both speech and finger data, the proportion of entrained cases is 0.3. Both measures that were based on the entrainment index (shown in the Mid and Best columns) yielded this proportion.

The remaining matter is relative phase. The finger and the speech movement experiments yield similar frequencies of the relative phase values (42%) of 0%, 25%, 50% and 75%, as Table **11.6** shows. The important point here is that the relative phase results for the speech and finger tasks were the same, across the experiments.

11.8 Submultiple and Multiple Ratio Results

Six arm and six brush experiments were conducted on seven subjects using a stimulus period that would be expected to yield entrainment at some ratio other than 1:1. In five experiments, the subjects produced submultiple data, that is, their period was at most half that of the stimulus, and in the remaining seven, the subjects produced a period at least double that of the stimulus. These experiments caused some subjects to vary their period radically across successive samples, but did not bring about continuous entrainment for any subject over the tested range. Entrainment is more readily achieved with a stimulus period that stands in a ratio of approximately unity to the subject period, rather than with higher integer ratios.

One subject (S9) moved her finger and repeated her syllable extremely slowly, as Tables **11.1** and **11.2** show. The stimuli were presented at half or a third or a quarter of her control trial period. Apparent entrainment in her data occurred by chance alone and she contributed no low EI values to the phase data.

11.9 Patterned Speech Results

Some subjects innocently lapsed into a rhythmic speaking pattern, especially if they relaxed to the point of dozing or were no longer vigilant. Although they eradicated the pattern when they noticed it, often it escaped their attention. Noticing the pattern was difficult as they were

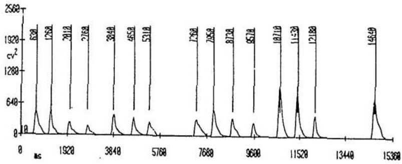

Figure 11.4 Patterned speech data from S11.

not able to hear their own voice.

Both subjects for whom patterning was a common incident organized their syllable production around the breathgroup (6 to 10 seconds long). One drew breath either every four, five, or six syllables quite consistently within an experiment. The other used a two bar pattern, with inhalation being the eighth beat of the second bar. Her data are shown in Figure **11.4**. It depicts one of the basic rhythmic patterns in English speech described by Martin (1972): the "Old MacDonald had a farm" pattern.

This virtually unconscious behavior occurs when the need to breathe occurs at one's intended moment of syllable articulation. This occurs at high repetition rates (short periods). The organization of syllable production around inhalation gave rise in S11's data to list intonation, manifest as regular energy differences between successive syllables, falling pitch on the last syllable in the group, and a pause for inhalation after articulating a group of syllables. Some subjects expanded their syllable into two feet. One, a subject whose data were discarded, added a final vowel, [ə]; others changed the vowel from a pure vowel to a diphthong.

The self-organization may be an indicator of the forcefulness of the stimulus rhythm. The period of S11's patterned repetition became more like that of the imposed arm movements in the speech-arm experiment (see Table **10.5**). Monosyllable repetition is probably comfortable only over a restricted range of periods, compared to the possibly larger range of comfortable finger movement periods. This is a reasonable proposition, since finger movement is not so directly powered by breath as is speech. There was no evidence of patterning in the finger movement data.

11.10 Subjects' Impressions

Commonly, subjects' performances did not match their impressions. This argues against the subjects' having successfully entrained or resisted entraining due to intention. No subject claimed to have deliberately entrained. Six subjects of the 13 who spoke about their strategy attempted, during at least one experiment, to maintain a specific rate, although they all said that they had not counted internally at any time (Ss 1, 4, 5, 9, 10, and 14). Four subjects (4, 9, 10, and 14) attempted to maintain a rate consistently within each experiment.

Of the 6 subjects who attempted to maintain a consistent rhythm, 2 remarked that eventually, they could not be sure what their originally preferred rate of movement had been (Ss 1 and 9). The imposed arm movement treatment was the most salient for those subjects. Two subjects (Ss 8 and 14) remarked in astonishment that the imposed arm movements thoroughly distracted their mind and their finger movements; one subject (S14) who had decided to keep to one rate of movement throughout each experiment was certain that he had not been able to do so in the finger-arm experiment although he claimed (incorrectly) to have maintained his preferred rate without interference from the stimulus rhythm in all the other experiments. One (S12) said that the arm movements made it easier to move the finger and that the finger felt heavier once the imposed arm movements ceased.

These subject impressions confirm the power of the imposed arm movement to drive the rhythm of the subject's finger movement. Since the subjects were so explicitly aware of their tendency to fall in with the imposed rhythm when the finger-arm combination was used, it probably was the experiment which provoked the most deliberate resistance to the stimulus rhythm. Thus, the results from the finger-arm experiment may underestimate the true power of the imposed arm movement rhythm to induce entrained finger movement.

It is surprising that some subjects believed that none of the experiments affected their rate of speech, when in fact both finger and speech entrained, and the speech task was associated with a stronger tendency toward entrainment than was the finger task in the arm experiments.

In addition, there was a common impression among subjects that the solenoid was practically insensible and had probably not influenced them. A number said that they did not notice it after the first minute or so. The solenoid provided many of the striking examples of entrainment.

It is safe to say, that regardless of the subjects' intentions, they tended commonly to be affected by the stimuli in the predicted ways. There was only one subject (S12) whose data did not show any influence of the treatments and whose period in the experiments tended to become more like that of the control condition. Clearly, when subjects were less forcibly aware of the kinesthetic stimulus rhythm, they were more susceptible to its influence.

There were clear and important differences between subjects. Some entrained in several experiments (S2, S4, S6, S7, S8, S11, S14 and S15). Generally, the subjects who dozed off or who were clearly relaxed tended to entrain, with one counter-example, S15, who was a very twitchy subject. The later experiments produced more evidence of entrainment, which was probably because subjects became more relaxed with every session.

11.11 Conclusions

Subjects tend to alter the period of their finger movements and syllable repetition so that they become more like the period of a concurrent kinesthetic stimulus in the absence of instruction to entrain to the stimulus. Entrainment arises in approximately 30% of all cases.

Overall, the effects of the stimuli upon the production of monosyllable repetitition and finger movement are similar, as predicted.

Virtually the same proportion of the subjects' periods in the speech and finger experiments changed to become more like the stimulus period. Speech and finger movement yielded the same numbers of cases of entrainment. The same proportions of the relative phase values of 0%, 25%, 50%, and 75% occurred in the stably entrained speech and finger movement data. The one anomaly, the strong evidence for entrainment in the speech-arm experiment, compared to the finger-arm experiment, is attributable to anomalous subject attitude in the finger-arm experiment.

A punctate stimulus on the skin yields more entrainment than a continuous stimulus on the skin, but the effect is not large, and should be replicated to verify its importance. The brush movement over the arm very consistently produced the least evidence of entrainment. However, the effect of the solenoid is not consistently much greater than that of the brush, across all measures used.

The stimulus that should have excited a large amount of afference induced more entrainment than a stimulus that could be presumed to be afference-poor. Imposing rhythmic arm movements tended to drive the subject's rhythm more strongly than brushing the skin. The effect was most pronounced in the speech experiments.

When the subject is instructed to move two or more body parts at different rates, theoretically the movements should move at harmonically related rates, and Kelso et al. (1981) provide evidence in support. However, Smith et al. (1986) have shown that entrainment between simultaneous monosyllable repetition and finger movement need not arise. They showed synchrony in 1 case of 8, and when the cases with close to harmonically related frequencies were included, 9/16 cases of entrainment (using their more liberal definition of entrainment).

When I paired voluntary movement of one limb (or of the speech organs) with involuntary (imposed) movement upon another limb, but did not instruct subjects to avoid entrainment, entrainment arose in 3/15 to 8/15 cases, depending upon the specific combination of task and stimulus.

The differences between the experiments were in the instructions and the use of imposed rather than voluntary limb movement. Even when subjects are instructed not to entrain (eg. Smith et al., 1986), they may entrain. Even when subjects must plan movements for only one group of body parts (eg. my work), they may entrain to concurrent movements of other body parts, without being instructed to do so. Despite the differences in methodology, my results and those of Smith et al. (1986) both show that speech movements and body movements can be weakly or strongly coupled; the strength of the coupling can be controlled by the subject.

It is worth noting that the coupling of finger and arm movements can be weakened more than Kelso et al. (1981) allow. Subjects certainly felt their finger being powerfully drawn to move at the rate of the imposed arm movement, but were able to resist entrainment. I suspect that resisting entrainment successfully required close vigilance in the finger-arm experiment.

The perceptual salience of the finger-arm combination deserves further investigation. An appropriate test of perceptual salience would be to conduct an experiment that included a condition in which subjects attempted to maintain a particular rate of movement, and another condition in which subjects concentrated closely upon the stimulus and attempted to maintain a particular rate of movement. Subject ratings for salience of the stimulus would also be required. That way the confound in interpreting the finger-arm experimental results (due to the subject's whims about resisting the stimulus rhythm in certain experiments) might be avoided. It is not a simple matter to inculcate in subjects identical attitudes to a task, particularly when one does not wish to instruct subjects to produce a particular type of movement as part of the task.

The entrainment seen here differs in character from that reported by Kelso and co-workers (1981; 1983; 1989; 1990) and by Baldissera, Cavallari, Marini & Tassone (1991), for the relative phase values reported in the literature on simultaneous voluntary movement are not preponderant. In particular, the relative phase of 0% (or synchrony), seen and emphasized as being fundamental in so much of the Kelso groups' work, is less common than phase values at antiphase (50%). It is worth noting that in Klapp's data (eg. 1981), antiphase seems to be the phase relationship most conducive to organizing <u>sensation</u>.

The prominence of phase values about antiphase for the arm and brush stimuli is not surprising. At antiphase, the arm movement would be at the changeover point between forearm adduction to abduction, surely a salient and important event for a perceptual system to note. The brush would also be changing direction at antiphase, from movement toward the elbow, to movement toward the wrist. Only with the solenoid would there be no event-like change to be noted at antiphase. Nonetheless, in the finger-solenoid data, the modal value is at antiphase. Even in the absence of an external event that could give rise to afference, antiphase is still important.

It is possible that interpretation of antiphase stimuli is easier than interpretation of in phase stimuli (based on Klapp et al., 1985). It is also possible that subjects were less aware of having entrained to stimuli that were directly out of phase with their movements. Those who did not wish to entrain might have avoided moving in phase with the stimulus. Clearly, more research is needed to discover whether the phase does depend on the sensory or motor nature of the task, and what part subject attitudes play.

Anticipation of the phase values of 0, 25, and 50% of the stimulus cycle is marked, and this has not previously been reported as being systematic, although it is clear from Ehrlich's data (1958) that subjects tend to anticipate a stimulus whose period changes predictably. All experiments except the speech-solenoid experiment showed that the phase commonly was in advance of one of the values commonly observed by other researchers. The most frequent phase value in each solenoid experiment was not anticipatory, and was one of the predicted phase values, ±5; FS: 50%, and SS: 0%.

I speculate that it may be relatively easy to predict precisely the time of punctate periodic events like a tap on the wrist, but with a more gradually changing stimulus one may respond to the early clues rather than wait until the changes have terminated. So, for example, when the forearm muscles begin to stretch or have stretched to a certain extent, one responds, rather than wait until the moment of maximum stretch, which would occur at the half or full cycle of arm movement (0 and 50%). This would make sense in adaptive terms; our senses facilitate purposeful action. They allow us to predict upcoming changes in the environment and to act to avoid or enhance their effect.

There has been considerable variation in the choice of measure in speech entrainment studies (eg. Morten et al., 1976; Fowler, 1980; Kelso & Tuller, 1984) and much argument from some workers (eg. Fowler, 1980). It has been tacitly assumed that one's measure might be theoretically important if peaks in the data align with the peaks that arise from other non-speech events, like a metronome tick. That sort of empirical validity has been achieved here, given the modal phase of 0% in the speech-solenoid experiment, and the general lack of difference between the finger and speech phase value patterns.

Past work on monosyllable repetition has noted that speech closely, rather than perfectly, entrains to a rhythmic stimulus (eg. Smith et al., 1986), although Kelso's work implies perfect entrainment of speech to finger movement (eg. Kelso et al., 1983). The results here not only show that speech need not entrain perfectly to a rhythmic stimulus, but also that finger movements need not do so either.

I have concentrated on the evidence for entrainment, but the remaining two thirds of the data are informative as well. Subjects who did not entrain (according to the definition here) did tend to change the period of their movement to be more like that of the stimulus period, or their period followed the stimulus period rather intensely, but briefly, and they did not generally adhere to the pattern of their control trend. These subjects are partly responsible for the strength of the results on the congruence of direction tests, even if their sequences of entrainment index values did not refute the null hypotheses.

The conclusions of this chapter are put into the context of the broad thesis in the next chapter.

CHAPTER 12
CONCLUSIONS

In Chapter **1**, I asked whether finger and speech movements were organized similarly, and according to non-linear oscillatory principles. The first hypothesis broached was that the capacity to sense position in the moving organs should be similarly accurate.

12.1 Kinesthesis in the Tongue

Sensing tongue and limb position appears to be similar in quality and source. This thesis has demonstrated the following with respect to lingual position sense in Chapters **2** to **7**:

1. Lingual position sense is available.
2. The sense of the tongue tip's position is as accurate as the sense of position displayed by other body parts. It is accurate to within 2^0.
3. The tongue's position is sensed both when people voluntarily move their tongue, and when their tongue is moved by an external agent.
4. The organs that convey position sense in the tongue probably include receptors in the tongue muscle and tendon. Previous

> research has indicated a role for the skin. The bias in position sense induced by loading the tongue points to a possible role in lingual kinesthesis for the corollary discharge.

In Chapter 7, it was pointed out that although the experiments on lingual kinesthesis probably tapped position sense, it is possible that instead the subjects analysed sensed tongue movement. From the point of view of the thesis, this ambiguity is interesting, but not crucial. It is the existence of lingual kinesthesis that matters; the psychological primacy of one kind of kinesthetic information, say, positional information, as opposed to another, for example information about extent of movement, is of secondary interest, as long as one sensation, say, of position, may be derived from another sensation, or directly from muscular afference. After all, a taxonomy of sensations has not yet been disentangled for even the more thoroughly explored kinesthetic sensations of the limbs, like position sense. Recent work shows that with slow (2^0/minute) imposed movement, finger position may be sensed even when movement is imperceptible, so movement sense and position sense should be distinct (eg. Clark et al., 1986; Taylor & McCloskey, 1990; Ferrell et al., in press). I did not look at such slow movements.

The second point to note is that position sense has been demonstrated for a new class of moveable organs. The tongue is unlike the bony segments or the eye, more common objects of kinesthetic investigation. Yet the enormous number of degrees of freedom for moving the tongue tip is monitored with similar accuracy to the accuracy associated with sensing limb movement and position, and the muscular bias that arises under load is no larger than that for the limb. The muscle spindles must be a reliable and trusted source of positional information, for subjects were biased in their judgment of the straight ahead after straining with the tongue muscles. Presumably, they need not have relied on the erroneous positional information from the tongue muscle, for contradictory and veridical information was presumably available from the mucosa of the tongue. Muscle may take on great importance as a source of information because there is neither joint nor rigid skeleton in the tongue.

I investigated lingual position sense following active and imposed tongue movement in horizontal and vertical planes, following tongue protrusion under a load, and during anesthesia of the lingual mucosa. My experiments demonstrated that in these various circumstances, lingual position sense was as accurate as sensing kinesthesis limb position.

12.2 Entrainment of Speech and Finger Movements to Rhythmic Stimuli

In consequence of the similarity of kinesthesis in tongue and limb, it was parsimonious to expect the movement of the tongue to be governed by similar principles as limb movement. It could be expected that sensory afference of various kinds should affect the organization of limb movements and speech movements in the same way. Chapters **8** to **11** demonstrated the following with respect to the organization of rhythmic finger and speech movements in the presence of a rhythmic kinesthetic stimulus. (Subjects were not instructed to synchronize their movements to those of the stimuli.)

1. The period of the subject's movement became more like that of a rhythmic kinesthetic stimulus to which the subject was exposed.
2. Entrainment to the kinesthetic stimulus occurred in 1/3 of the experiments, and occurs commonly outside the range of ±15% of the subject's preferred period in a control trial.
3. A relative phase slightly in advance of 50% (slightly in advance of 180°) of the stimulus cycle endpoint was the most common relationship between the subject and stimulus movement cycles. The subject's movement tended to be in advance (by

10% of the stimulus period) of the relative phase values of 0%, 25% and 50%, which have often been observed in entrainment experiments.

4. The punctate stimulus, such as a tap on the skin, attracted the subject's period of speech movement more than did the continuous stimulus, such as brushing the skin. The difference between the effects of the punctate and continuous stimuli is small.
5. The stimulus that gave rise to afference from numerous sources (imposed rhythmic arm movement) attracted the subjects' period more strongly than the stimulus that excited one source of afference, (brushing the skin). The effect of the imposed arm movement upon the period of monosyllable repetition was especially notable, on all measures.
6. Speech and finger movement rhythms tend to be influenced similarly by the rhythmic kinesthetic stimuli.

The two main hypotheses have been upheld: entrainment commonly occurs, and speech and finger movement rhythms were similarly influenced by the different kinds of kinesthetic afference. Rhythmic movement is organized by kinesthetic sensation similarly for speech and finger movements.

There was one difference between speech and finger movement: the extent of entrainment in the finger-arm and speech-arm experiments.

Chapter **11** (section **11.10**) indicates that three subjects sensed that the rhythm of their finger movements was being strongly attracted by the rhythm of the imposed arm movements, and six admitted that they had attempted at some point in at least one experiment to maintain a consistent rhythm, resisting the imposed rhythm.

The sense of unwilled attraction to the kinesthetic rhythm did not mark the speech experiments or the other finger movement experiments. It is not surprising that subjects were so strongly aware of the tendency of their finger and arm movements to synchronize, and were less aware of any impinging of the stimulus rhythm upon monosyllable repetition. The imposed arm movements may yield afference for organizing finger movement that the subject considers highly relevant (see Hasan & Stuart, 1988), even if the two arms are not working as a pair on a particular motor task. Even though the moving arm and finger were on different sides of the body in the experiments here, they are part of a pair of limbs. In what follows, a pair of limbs refers to two limbs that attach symmetrically about the mid-saggital plane of the body, correspond in structure, and that commonly work together to achieve a goal, for example, the two arms. The afference due to both would be similar in kind, arising from arm and finger muscles, skin and tendons, and the locations of its origin would be nearly symmetrical about the mid-saggital plane. In normal circumstances, afference from one limb of a pair might well be interpreted in the light of afference from the other member of the pair, since they so commonly work together to hold and lift objects. The very strong coupling between organizing voluntary movements of the two arms (eg. Kelso et al., 1979; Kelso et al., 1981) would lead one to expect that coupling between voluntary and involuntary movements of the arms, and therefore coupling of the afference from both might also be particularly strong.

It is strange that the attraction of the imposed arm movement rhythm was not sensed as being at all peremptory in the organization of speech movements, since about half of the subjects entrained in the speech-arm experiment. The findings suggest that a stimulus' salience, and the attention paid to it, may not be reliable indicators of its ability to induce entrainment. Attention here probably served to elicit resistance to entrainment.

It is probably the case that for tasks requiring simple rhythmic movements attention is not always needed to organize movement once the task loses its novelty. Afference due to an external stimulus can organize the rhythm of repeated voluntary movement in the absence of will. This susceptibility to environmental stimuli should be an advantage for any animal. A responsive motor-sensory system is useful. It allows us to adapt to unforeseen changes in the environment, and to accommodate many relatively familiar environmental contingencies without thinking about them. It allows us to drive a car over a familiar route without paying much attention, stopping at the red traffic lights, and passing through the green ones. The stimulus rhythms in my experiments may serve as environmental contingencies for the subjects.

At the same time, it would not be useful to an animal for its motor system to be enslaved by incoming afference. Then the animal would no longer be free to act, or to decide to move for a reason. Thus, voluntary movements must be able to be planned independently of concurrent sensory rhythms when the animal so requires, but should otherwise be open to their influence. If the motor planner can incorporate into or exclude afferent rhythm from the motor plan, then the results that I received can be explained. Entrainment to a rhythmic stimulus need not occur, but will tend to arise as the default behavior when the movement task does not preclude it. This is precisely the interpretation that fits Smith et al.'s (1986) results as well. Inescapable entrainment to every rhythmic sensory stimulus might not serve the animal's purpose when the animal has a specific goal for its actions.

It is important that the sensory afference arising from the stimulus need not be relevant in any obvious way to performance of the task for it to induce entrainment. This is one of the major findings of this thesis. This result powerfully implies pervasive application of non-linear oscillatory principles to interpretation of sensation for the purpose of organizing movement. The stimulation that arises from the rhythm of the solenoid, brush or imposed arm movement is not in any obvious way relevant for speech production. There is no likely benefit to the subject from entrainment, other than ease of movement organization. Yet, the rhythm of monosyllable repetition was strongly affected by the imposed arm movement rhythm. I suspect, in keeping with what others have proposed (eg. Baldissera et al., 1991) that ease of organization is an important factor in rhythmic movement tasks.

12.3 Findings in Reference to Previous Work

These results permit a clearer interpretation of previous work. In the main, previous work (eg. Kelso et al., 1981; Kelso et al., 1983; Smith et al., 1986; Scholz & Kelso, 1989 and 1990) has not kept separate the sensory and the motor influences on movement. The experiments here have carefully rectified that imprecision.

Equally importantly, employing kinesthetic rhythms has broadened the acknowleged reach of afferent influences on movement organization. Many investigations of entrainment use standard auditory rhythmic sources, such as metronomes (eg. Hary & Moore, 1987, Scholz & Kelso, 1989 and 1990; Baldissera et al., 1991). The successful introduction of kinesthetic rhythms into the field widens the scope of future work, and deepens the significance of past results. Clearly, the relationship between afference and movement organization is both intimate and pervasive. It is intimate in that movement rhythm can be organized by afference without the conscious subject being aware of it. It is pervasive too: just because normal speakers apprehend speech by ear does not mean that sound alone can manipulate speech rhythm. Kinesthetic afference can drive the rhythm of syllable repetition.

Entrainment of a moving limb to a sensory stimulus or to a simultaneously moving body part has been discussed in one guise or another for some time (for example, as problematic interference: eg. Hiscock & Chipuer, 1986; as due to limited resources for movement planning: eg. Klapp, 1979; Klapp et al., 1981; as a showcase for non-linear oscillatory principles at work: eg. Kelso et al., 1981), but very limited discussion of the necessary and sufficient stimuli for entrainment has ensued. With the investigation of punctate and continuous stimuli, and of afference-rich and afference-poor stimuli here, a proper start has been made in that area.

While all stimuli induced entrainment to some extent, the afference-rich imposed arm movement treatment clearly yielded the strongest perception on the subjects' part of their finger's unwilled attraction too the stimulus rhythm, and also the most evidence for entrainment in association with the speech task. Hasan & Stuart (1988) proposed that afference from passive antagonist muscles was likely to be as important as that from the active movers. The data provide material for stronger claims than that, for the afference in the imposed arm movement experiments arose from passive muscles in other body parts (not the speech organs), and monosyllable repetition nonetheless entrained.

The following points about entrainment can be made. First, synchrony is difficult to avoid when two limbs of a pair are voluntarily moved simultaneously by the subject (Kelso et al., 1981, the discordant rhythm task). Second, synchrony is not mandatory when speech articulators and a limb are voluntarily moved simultaneously (Smith et al., 1986). Thus, the rigid synchrony that was claimed to mark simultaneous limb movement in general (Kelso et al., 1981) may be particular to the cases of voluntarily moved paired limbs performing tasks with similar functions. Third, synchrony is not mandatory, but is common when the subject moves the speech articulators voluntarily while arm movement is imposed. In the absence of instruction, kinesthetic sensation induces entrainment of monosyllable repetition somewhat less forcefully than does concurrent voluntary limb movement, to judge from Smith et al.'s (1986) results.

The phase relationship of subject to stimulus movement was not as Kelso and coworkers predicted (eg. 1981, 1983), but rather more in line with Klapp and coworkers' findings (eg. 1981, 1985). Klapp et al. found that an antiphase relationship (50% or 180°) yielded the fewest errors in his subjects' monitoring of two rhythmic stimuli. The tendency toward antiphase relationships in Klapp et al.'s data and my data does not yet have a good explanation. Klapp et al. (1985) have rejected processing restrictions as a reason.

This thesis used data analysis techniques that improve upon those of previous researchers in speech entrainment studies, particularly those of Smith et al. (1986). The improvements are described in Appendix 3.

12.4 Non-Linear Oscillatory Principles and the Motor Plan

The central thesis has been upheld. The non-linear oscillatory metaphor holds for finger movement and for speech movements. The evidence of entrainment to a kinesthetic rhythm makes a potent argument for the timing of repeated movement being organized in accordance with non-linear oscillatory principles. Were movement under regulation by linear, rather than non-linear, oscillators, subjects would have performed without variability in the control conditions, would not have unknowingly altered the period of their speech and finger movements to agree more closely with those of the stimulus, nor would they have acknowledged any attraction to the rhythm of the stimuli. Of course, if movement were not oscillatory at any level, the rhythm of the stimulus should not have influenced the subjects' rhythms.

It is possible to think in terms of default parameterization of the motor plan. Let us accept that the default is to couple the two moving systems of interest, for example, the finger and the speech articulators. It should be possible for the subject to specify that the coupling is to be weakened. From the foregoing, we might speculate that the subject finds it easier to weaken the coupling if the main members do not belong to a pair or are anatomically contiguous. Future experimentation could help to decide whether this anatomical factor is important.

The motor system should, by default, allow sensory afference to organize the rhythm of movement. The coupling might then be stronger when the sources of sensory afference are numerous, as in the speech-arm experiment, and/or when the afference seems potentially relevant, as in the finger-arm experiment. Further experiments on subject attitude and entrainment using limbs that are members of a pair, and those that are not would be required to understand what constitutes 'relevant'.

It is in any case unlikely that subjects have a rigid internal timekeeper. The period of the subjects' monosyllable repetition and finger movement was fairly variable in the control conditions, and across days. The ability to vary one's rhythm is no doubt beneficial to us as animals, for it allows adaptation. Movement would become inefficient if its rhythmic basis could not be tuned by internal constraints, such as inhalation, or by external limitations, such as the speed of a conveyor belt in an assembly line, or the size of a bolus of food. Cruse, Dean, Heuer & Schmidt (1990) have stated that sensory information may define the time axis on which a motor program operates. The data here support that remark. One of the parameters of the motor plan should be period (or frequency).

The motor plan exploits rhythm. For example, it might use a central pattern generator or a set of coupled non-linear oscillators (Gracco & Abbs, 1986; Bock, 1990). In addition, the motor plan may hold open the afferent floodgates to the rhythm generators, whatever and wherever they may be. Theoretical relegation of afferent information to reflex channels with purely peripheral effects is not defensible, given the results here. The solenoid tap on the skin, in order to induce entrainment of speech movements, must surely act via high level sensory afference. One of the few models to recognize the long reach of afferent influence in the organization of movement is that of Katz & Harris-Warrick (1990). Although this model is derived from physiological experimentation on decapod crustaceans, its essence is the flow of afferent information from the periphery into a series of central coupled rhythm generators. The work here provides human behavioral evidence that concurs with the idea that the afference influences the generation of rhythm, at whatever level of the nervous system the pattern generators may be found.

From the above, the contributors to the motor plan would include a sensory-motor register of the body surface and limb location relative to the trunk, or of tongue location relative to the head. This register would be open to change via afference. It seems likely that spatial information would be registered, and that it should be available to the motor plan for organizing movement. The bias induced in tongue positioning after loading strongly supports this suggestion.

The rhythmic source that is at the disposal of the motor plan for the purpose of timing movement can be influenced, or possibly set up, by an incoming sensory rhythm. Memory should also be required generally for organizing movements. Contributors to a motor plan from memory include the plans for previously successful movements, as Chapter **1** argued.

In sum, kinesthesis provides information to help plan a voluntary movement, and is available to regulate rhythmic movement while it is being executed, altering movement control parameters as necessary. The strength of its influence is under the control of the subject to some extent. When kinesthesis exerts a very powerful and attention-grabbing influence, as in the case of simultaneous rhythmic imposed and voluntary movement of limbs that comprise a pair, then vigilance and intention can help the subject to weaken the influence of kinesthesis on the movement.

12.5 Implications for Stuttering Therapy

It may be the case that a congruent rhythm restores fluency to the disfluent. Stutterers are thought to have trouble with timing a succession of speech events (van Riper & Emerick, 1984). One of the professional treatments recommends vivacious gesticulation by the stutterer as an accompaniment to speech (eg. Wingate, 1976; Garcia-Moreno, 1984). This approach represents a way of acknowledging or setting up bodily a rhythm that allows the stutterer to organize fluent speech. The normal speaker must be presumed to be able to specify unthinkingly the rhythmic basis for fluent speech. However, the stutterer may need to set up a rhythm for speech in more deliberate fashion or complement a fragmented or frangible rhythm with accompaniment from the repertoire of (presumably more fluent) body movements. If this is so, then gesticulation as such is not the quintessence of the solution. Rather, accompaniment with any fluent rhythmic body movement pattern should suffice.

This argument has implications for the interpretation of the speech-arm experiment results. I have assumed that the considerable evidence of entrainment that the speech-arm experiment provided was not due to any special strength of the speech-arm combination, but to subject attitude having lessened the effect of the finger-arm treatment. It is also possible that the speech-arm combination is especially potent, for the imposed arm movements did describe a fluent rhythm, and would be the sort of body movement, but under voluntary control, that a therapist might recommend to a stutterer (see Wingate, 1976). It would be worth knowing whether imposed limb movement and voluntary limb movement do reduce stuttering, and whether the voluntary or involuntary movement is the more effective.

12.6 The Units Used by the Motor Plan

The unit of movement that the motor plan uses remains unknown. Some subjects occasionally moved their fingers in cycles that clearly began and ended at the bottom of the swing; others sometimes halted at the top of the swing. The form of the finger movement does not suggest any one unit that the motor plan might favor. Other research also fails to find consistency in the form of voluntary limb movement that might suggest an underlying unit of production (eg. Cruse et al., 1990).

Subjects' speech also exhibited different patterns. Often the vowel varied, and sometimes the consonant changed, or disyllabification occurred. Thus, even if, as Kozhevnikov & Chistovich (1965) and Fowler (1983) claim, the consonant-vowel pair is a basic unit of programming in speech, that unit is not stable in production. Here, one subject, whose data were discarded, appended [ə] to each monosyllable. Other subjects on occasion created a diphthong from the vowel.

The apparent elasticity of the monosyllable in production and the favoring of different endpoints in the finger movement cycle suggest that the subjects may have the unit of programming at their disposal, within limits. The same type of movement may have different functions, depending upon the task at hand, as Chapter **1** pointed out. When there is no particular function for a simple movement, the subject possibly organizes the movement so that it is as easy to execute as possible. The criteria for 'easy' may change over seven minutes, or the subject may become bored with the movement and seek a change just for variety. In any case, the motor system seems to be flexible. Either it can plan using various units, or, if the units are fixed, it can introduce a new, subordinate meter in the production of the unit. I favor the first possibility because diphthongization of a vowel would seem to require the propagation of a new, lower level of unit from a higher one. The case for the other possible explanation, a dormant diphthong in the monsyllable, seems weak.

12.7 Summary

Ten experiments, four on lingual position sense, and six on the entrainment of speech and finger movement to kinesthetic rhythms, supported the thesis. The position of at least one speech articulator, the tongue, can be sensed as accurately as limb position is sensed. The kinesthetic organs in the tongue and limb, particularly the muscle, tendons and corollary discharge, may operate similarly to convey position. The thesis that speech movements and finger movements could be organized similarly was upheld with respect to a spatial aspect of movement planning, position sense.

With respect to organizing movement timing, syllable repetition and cyclic finger movement demonstrated similar susceptibility to influence from a kinesthetic rhythm. The subjects entrained their syllable repetition and finger movement to the kinesthetic stimuli in one third of the experiments. A punctate stimulus, like a tap on the skin, tends to induce more entrainment than does a continuous stimulus brushing back and forth on the skin, but the difference in effects is small. An afference-rich stimulus (imposed arm movement) induces entrainment more frequently than does an afference-poor stimulus (imposed brush movements over the skin). The speech and finger movement tasks were associated with similar amounts of entrainment.

These experiments have major import for three basic reasons. First, they show the pervasive grasp of sensory information upon movement planning and control, which counters the view that motor patterns are blind to sensory influence. Second, they at the same time support the non-linear oscillator as a central tenet of movement organization. Third, they suggest that speech and voluntary limb movement are similarly organized, and should not necessarily be treated separately by students of movement.

Most importantly, the demonstrations of the availability of kinesthetic sensation in the tongue, the influence of kinesthetic rhythm on the rhythm of monosyllable repetition greatly bolster the argument for the susceptibility of speech to organization, at least in part, by kinesthesis. Clearly, voluntary speech movements in monosyllable repetition are not exempt from kinesthetic control, and do not need to be accorded special theoretical status with respect to this non-linguistic level of movement organization. Organizing <u>fluent</u> speech may require some unique theoretical provisions, notwithstanding.

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APPENDIX 1

SCHEMATICS OF EXPERIMENTAL EQUIPMENT

The apparatus for recording the solenoid, arm, brush and finger movement cycle endpoint is given in Figure **A1.1**.

The output of the light detector gated noise from the noise generator into the amplifier. From there the amplified noise was recorded onto videocassette tape. When the solenoid was used, the output of the function generator gated the noise from the noise generator to the amplifier.

A comparison of the reponse times for the light detector system, the solenoid tap, and the microphone was carried out by recording with the microphone the sounds made by the solenoid striking an object at full extension, and an object passing the center of the light detector at the speed of the finger. The recordings of the sound via the microphone and of the event via the gate box system depicted above produced simultaneous onsets (within the 30 ms window of the analysis programs, for example, spl.c (see Appendix **2**)).

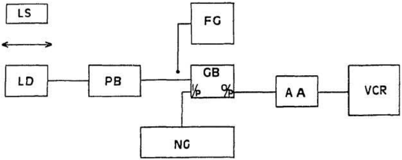

Figure A1.1 Recording Apparatus for all stimulus rhythms and the finger rhythm. LS: Light Source LD: Light Detector PB: Photo Box GB: Gate Box FG: Function Generator NG: Noise Generator AA: Audio Amplifier VCR: Video Cassette Recorder. The arrow represents the movement of the arm, brush, or finger through the light detector system.

APPENDIX 2

ANALYTICAL PROCEDURES AND COMPUTER PROGRAMS

A2.1 Analytical Procedures

The analytical procedures described below were followed by using computer programs. Programs Spl (or twobar, sol, or solfin, as appropriate) collected 15.4 seconds of amplitude-time data from the audio channels of a videocassette recorder, smoothed it, converted it to intensity data, picked out the peak intensities in the speech, and calculated the time of the maximum excursion of the finger or stimulus movement. The times of the speech peaks or the maximum excursion of the finger or stimulus movement were saved in datafiles.

Program Freq calculated the mean period and standard deviation for each 15.4 second sample of subject and stimulus movement, using the datafiles produced by spl. From the mean periods, the preliminary form of the entrainment index was calculated (see Appendix 3). Mean relative phase and its variance were also calculated.

Program Small allowed the playback of 2.2 seconds of data and was used to check the data when there were any concerns, for example, about the presence of background noise, or about the presence of coughing or sneezing, rather than monosyllable repetition. Small also served to ensure that the conversion of amplitude to intensity did not result in displacement of the data peaks in the two sets of data with respect to each other.

A2.1.1 Amplitude and intensity

Amplitude is the commonly employed measure in entrainment experiments (eg. Kelso et al., 1981; Smith et al., 1986). I wished to be able to compare my results in a straightforward way to those in the literature. Finger movement and speech results are susceptible to relatively transparent comparison if the measure is amplitude or its derivative.

Intensity was calculated from the amplitude values. It produced a compressed scale that virtually eliminated unwanted noise at the low end, while enhancing peaks at the high end of the amplitude scale. The relationship between the amplitude contour and the derived intensity contour is shown in Figure **10.6** (output of program small).

A2.1.2 Sampling procedures in spl

A2.1.2.1 Digitization.

The amplitude data were calculated, using spl, by taking a sample every 30 msec of 128 voltages coming in each channel of the analog to digital board. Two mean values, one for the data in each channel, were calculated immediately, producing one amplitude datum per channel before the next 128 voltages were digitized. Essentially, this served to reduce the data and smooth it, preliminary to manipulation. Sampling every 30 ms per channel allowed the reliable derivation of a smooth intensity envelope. Occasional checks of the original amplitude data against the intensity envelope were conducted by playing back 2.2 second sections of digitized speech through a loudspeaker, using small. Small did not reduce the amplitude data during digitization, and used the same method as spl to derive the intensity envelope.

A2.1.2.3 Smoothing

Amplitude data were smoothed by moving across the data one point at a time, averaging across 3 consecutive amplitude data and replacing the middle (second) datum with the new mean. This was carried out twice for all amplitude data. The smoothing reduced the height of the steep narrow peaks associated with the onset of stop consonants, while preserving the location of the amplitude peaks on the vowels.

A2.1.2.2 Conversion to intensity values

The digitized, averaged, and smoothed amplitude data were converted to units of intensity (centivolts squared). The equation for converting amplitude to intensity is:

$$P = (A / 8)^2 \qquad (1)$$

where P represents intensity value in centivolts^2, and A the amplitude. 8 is the constant divisor required to convert the amplitude value from the analog-to-digital board to centivolts.

Gated noise represented the finger, brush, arm, and solenoid movements. It was collected and digitized as described above. The actual intensity values for the gated noise data were not of interest. The maximum intensity value was substituted for every datum over the sections where the noise was gated on.

A2.1.2.4 Peak picking

The maximum intensity value in every sequence of 2 or more non-zero intensity values (60 ms) between 2 intensity values equal to 0 defined a peak in the speech data. In the non-speech data the peak represented the maximum excursion of the finger (brush, arm) movement cycle. This peak was inferred to be at the point equidistant between the midpoints of each narrowly separated pair of data bars (that is, where the noise has been gated through to the videocassette tape). The midpoint of a data bar was calculated as the point equidistant between the first and last non-zero values for intensity. Figure **A2.1** demonstrates the placement of midpoints (a) and (b) for two bars, and the subsequent placement of the peak representing the maximum excursion (c).

For the solenoid, calculating the time of occurrence of the peak indicating maximum excursion required calculating the midpoint of the single bar that resulted from the gating of noise.

To maximize precision in the data with paired bars (finger, brush and arm experiments), the light detector system was set to allow about a three sample (90 msec) gap between a pass back and forth at the expected top speed of the stimulus or subject movement. The precision was

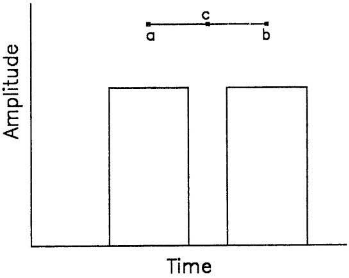

Figure A2.1 Calculation of the time of occurrence of peaks in the data from the light detector system (finger, brush and arm data). (a) and (b): midpoints of bars. (c): midpoint between (a) and (b).

generally good, as Figure **10.7** suggests. The brush and arm movements were equally fast approaching and leaving the point of furthest travel, so error in determining the time at which that point was reached should be small. The speed of finger movement was symmetric about the bottom of the swing.

In data checks conducted after smoothing and conversion to intensity units, variation in the relative temporal locations of the peaks across different digitizations of the same recording was small, on average 15 ms. This is the minimum difference that could be expected, given that the digitization procedure segments the speech at different locations during each digitization.

These peaks were the basis for all calculations of period. The time of occurrence of the maximum intensity in speech data, and of the midpoints in or between noise sections in the non-speech data was the essential matter, and the times of occurrence were recorded in datafiles. Freq calculated statistics from these.

A2.2 Programs Spl, Freq, Small

The peak picking algorithm is given in spl. It reliably allocated a peak to the same relative location in a 15 second sample of speech intensity, namely, where the vowel energy was greatest.

SPL.C

```
/* Program which records a point about once every 30 msec from 2
channels, for a total of 15.36 sec. The amplitude over every BUFLEN
(usually 128) points is averaged DURING recording, producing envelopes
of 512 points * 2, which can be transformed to intensity envelopes.
Intensity peaks are picked out by imposing a threshold at 1/10 maximum
intensity on the data.  The threshold is level, but can be set to decline
over the breathgroup (speech channel 1, stimulus data Channel 0).
Intensity data and peaks can be saved onto disk, graphed on screen, or
sent to a plotter. Playback through DACs and checks of the raw data can
be done with SMALL.C.
     This version is specifically for use with the light detector.
     Property of C.Grover, Department of Psychology, Memorial
University of Newfoundland. */

#define        LINT_ARGS
#include      <stdio.h>
#include      <stdlib.h>
#include      <string.h>
#include      <malloc.h>
#include      <math.h>
#include      <herc.h>
#include        "tek.h"

#define max(a,b)  (((a) > (b)) ? (a) : (b))
#define min(a,b)  (((a) < (b)) ? (a) : (b))
#define abs(a)          (((a) < 0) ? -(a) : (a))
#define sqr(a)          (a * a)
#define             SUCCESS  0       /* general-purpose return codes */
#define             FAILURE          (-1)
#define             YES         0
#define             NO          (-1)
#define        LESS_THAN       <
#define        MORE_THAN        >
#define        EQ              ==
```

```
#define            MASTER
#include     <labhead.h>
extern int labpac(int,...);

#define            SWEEPS          512   /* points in envelope */
/* ---------- globals ---------- */
double TEMP1, TEMP2;
int far * BUFFER = (int far *) 0x80000000;
                              /* assume area above 512K unused */
int BUFLEN;
int AMPL[SWEEPS][2], POWER[SWEEPS][2];
/* BUFLEN is analogous to LENV in small.c */
int FROM, POINTS;
int A[80][4];
int BR[60];
int CALC = 0;
int MAX_PK, MAX_PK0, MAX_PK1;
int STBG = 0;
int BGP = 511;
int FLAG = 0;
int TDIV;
int W = 5, WLIST[6] = {1, 2, 5, 10, 20, 40};
/* first element in this series would have index = 0. 40 = usual value */
int ADIV = 4;
/* amplitude selector */
int PEAK_UP = 0; /* PEAKS AT BOTTOM, IN NARROW GAP */
char DATE[11];
char INTFILE[15];
char FILENAME[15];
float TFACTOR = 10.0;     float TFACTOR0, TFACTOR1;
double SLOPE, SLOPE0, SLOPE1;
double XSCALE;
#define GRID ( (char far *) 0xb8000000)
/* ---------- declining threshold function --- */
/*
dec (j)
```

```
int j;
{
int t;

        t =(int) (((float)MAX_PK- (((10.00 -TFACTOR)/10.0)
*(float)MAX_PK))
                -((float)j* SLOPE));
        if (t < 0) t = 0;
        return(t);
}
*/
/* ---------- Keyboard BUFFER flush ---------- */
void kb_flush ()
{
        while ( (char) bdos (0x0B, 0, 0) ) getch ();
}

/* ---------- check for a loaded vector ---------- */
/* Is LabPac there? If so, there should be a vector for INT 0x66. */
void check_vector(v)
        int v;
{
        unsigned long far * zero = 0x00000000;

        if (v < 0 || v > 255) {
                printf ("No such interrupt.\n");
                exit(FAILURE);
        }

        if ( *(zero + v) == 0L) {
                printf ("ERROR: Vector %xH isn't loaded.%c\n", v, 7);
                exit(FAILURE);
        }
}
/* ---------- long-to-pointer conversions ---------- */
union HUGE_PTR {
```

```
        int huge * ptr;
        unsigned int i[2];
};

int huge * ltop (a)
        unsigned long a;
{
        union HUGE_PTR p;
        p.i[0] = a % 16;
        p.i[1] = a / 16;
        return (p.ptr);
}

unsigned long ptol (p)
        union HUGE_PTR p;
{
        unsigned long a;
        a   = p.i[1];
        a <<= 4;
        a  += p.i[0];
        return (a);
}
/* ---------- record sound sample ---------- */
int record ()

{
        static int gain[8] = { 0,0,0,0, 0,0,0,0 };
        char ch, input[4], filename[15];
        int oldintr, result, mean0, mean1, nku, j;
        register int m, k;
        long int tot0, tot1;
        unsigned int offset;
        int far *pointer;

        printf ("There is room for %d points of envelope.\n\n",
              SWEEPS);
```

```
/*      printf ("Press ENTER to begin.\n\n");
        kb_flush();
        do { } while ( getch() != 13);
*/
        /*- LabMaster board initialisation functions - */
        result = labpac (RESET);
        result = labpac (TIINIT, TIMER);

        /* eight input channels; DMA channel 1 */
        result = labpac (AIINIT, ATOD, 8, 1, gain);

        printf ("TDIV = 7,  BUFLEN = 128\n");
        TDIV = 7;          BUFLEN = 128;

        /* printf ("TDIV parameter (Hit ENTER for default =
              7).\n");
        if (getch() == '\r') TDIV = 7;
        else TDIV = atoi(gets(input));  */
                  /* use TDIV as frequency divisor */

        /* printf ("BUFFER length (64, 128, 256, 512).\n");
        printf ("Hit ENTER for default = 128.\n");
        if (getch() == '\r') BUFLEN = 128;
        else BUFLEN = atoi(gets(input)); */
              /* use BUFLEN as number of samples taken */

        printf ("Hit ENTER to record for 15.36 seconds.\n");
              /* --15.36 = 1 sec/33.3 ticks/sec * SWEEPS */

        kb_flush();
        do { } while (getch () != '\r');

/* timer 5 controls basic sampling rate of 100 kHz / (TDIV (usually 7) *
2 channels) = 7.143 kHz sampling rate per chnl. The actual sampling
rate has been measured as being closer to 7.2 kHz. Sampling is done at
this rate once every 30 ms (controlled by timer 2, counted by timer 3).
```

```
Each 30 ms sweep comprises BUFLEN (usually 128) readings. A total of
usually 512 SWEEPS are made = 15360 ms record time. AMPL =
measure of mean amplitude over k points. [0] for other, [1] for speech.
Square produces measure of mean power, saved as POWER.*/


    labpac (TIST, 2, 15, 3);  /* 15 = 100 Hz.
                                  /3 = 33.3 Hz.*/
                    /* was /4 = 25 Hz CHANGED 3/1/90 */
    labpac (TIST, 3,  0,  0);  /* counter of timer 2 */
    labpac (TIST, 5, 12, TDIV);  /* 12 == 100 kHz */

    nku = 0;
    pointer = BUFFER;
    offset = BUFLEN * 2; /* integers per scan */

    cls();
    printf ("\n\n\t R E C O R D I N G . . . (takes 15.36
          sec)\n\n");
    oldintr = labpac (INTCLR, 255);
          /* turn off all interrupts */

    for (j = 0; j < SWEEPS; j++) {
          pointer = BUFFER + (j&1) * offset;
          labpac (TISTAT, 3, j);  /* time for a sweep? */
          labpac (TIST, 4, 3, 0);  /* count conversions */
          result = labpac (AIDMA, 0, BUFLEN, 2, pointer);
          if (result) {
                printf ("AIDMA error = %xH.\n", result);
                labpac (INTSET, oldintr);
                labpac (RESET);
                return (FAILURE);
          }

          /* ---------- work up previous sweep ---------- */
          if (j>0) {
```

```
        pointer = BUFFER + ((j-1) & 1) * offset;
        tot0 = 0L;
        tot1 = 0L;
        for (k=0; k<BUFLEN; k++) {
            /* tot0 += (int) abs (*pointer++); */
            /* tot1 += (int) abs (*pointer++); */
            /* Inline replacement of abs() call.
            * SEE: stdio.h file from Alcyon compiler
            * for Atari ST */

            m = *pointer++;
            tot0 += ((m) < 0 ? -(m) : (m));
            m = *pointer++;
            tot1 += ((m) < 0 ? -(m) : (m));
        }
        AMPL[j][0] = (long) tot0 / BUFLEN;
        AMPL[j][1] = (long) tot1 / BUFLEN;
    }

    if ( labpac (TIRAW, 3) > j+1) nku++;

    labpac (TISTAT, 4, BUFLEN*2);
    labpac (TIAB, 4);
}

labpac (INTSET, oldintr);      /* restore interrupts */
printf ("%c\n\n\tRecording done.\n", 7);
if (nku > 0) printf ("Data bad; %d points measured
    late.\n", nku);

labpac (TIAB, 2);
labpac (TIAB, 3);
labpac (TIAB, 5);

/* ---------- now get the last sweep ---------- */
pointer = BUFFER + ((SWEEPS-1) & 1) * offset;
```

```
        tot0 = 0L;
        tot1 = 0L;
        for (k=0; k<BUFLEN; k++) {
              tot0 += abs (*pointer++);
              tot1 += abs (*pointer++);
        }
        AMPL[SWEEPS-1][0] = (long) tot0 / BUFLEN;
        AMPL[SWEEPS-1][1] = (long) tot1 / BUFLEN;

        /* ---------- fix any DC offset ---------- */
/*      pointer = BUFFER + ((SWEEPS-1) & 1) * offset;
 *      tot0 = 0L;
 *      tot1 = 0L;
 *      for (k=0; k<BUFLEN; k++) {
 *            tot0 += *pointer++;
 *            tot1 += *pointer++;
 *      }
 *      mean0 = (long) tot0 / BUFLEN;
 *      mean1 = (long) tot1 / BUFLEN;
 *
 *      for (k=0; k<SWEEPS; k++) {
 *            AMPL[k][0] -= mean0;
 *            AMPL[k][1] -= mean1;
 *      }
 */
        CALC = 0;
        FLAG = 0;
        STBG = 0;
        BGP = 511;
        return (SUCCESS);
}
/*- two scope-like grids, 4 div high * 10 div wide -- */
void make_grid()
{
        int j;
```

```
for (j =  10; j < 171; j + = 40) hor_line (0, j, 500, j,
      1);
for (j = 180; j < 341; j + = 40) hor_line (0, j, 500, j,
      1);

for (j =   0; j < 501; j + = 50) {
      line ( j,  10, j, 170, 1);
      line ( j, 180, j, 340, 1);
}
Ggoto_xy (3, 64);
      gtext ("FROM");

Ggoto_xy (5, 64);
      gtext ("POINTS");

Ggoto_xy (7, 64);
if (PEAK_UP < 1) gtext ("NARROW");
else gtext ("WIDE");

Ggoto_xy (9, 64);
gtext ("TFACTOR1");

Ggoto_xy (11, 64);
gtext ("SLOPE1");

Ggoto_xy (13, 64);
gtext ("BGP");

Ggoto_xy (15, 65);
gtext ("power data");

Ggoto_xy (17, 65);
gtext ("Page ___ of __");

Ggoto_xy (19, 65);
gtext ("CV2/div ______");
```

```
      Ggoto_xy (21, 65);
      gtext ("Pts/div _____");
}
/* ----- smoothing --------------------------------- */
void smooth (Array)
 int Array[SWEEPS][2];
{
      int j, k;
    int smth[SWEEPS];
      float mn_str, sum_str, old_pt, new_pt;

/* First AMPL passed as Array, then smoothed AMPL passed
as POWER. div by 8 to keep number less than 32768 before square. 1/8
for A-D to cv conversion. smoothing over 3 points twice (to maintain
peaks in true location) and discount of peaks with very steep onset, as
these are likely to be due to stop consonant release, not vowel energy. */

      for (k = 0; k < 2; k++) {
           sum_str = 0;
                  for (j = 0; j < 3; j++) {
                  mn_str = (Array[j+FROM][k]);
                  sum_str = sum_str + mn_str;
                  }
           mn_str = (float) sum_str / 3;
           smth[0] = (int) mn_str;
           smth[1] = (int) mn_str;

           for (j = 0; j < (POINTS - 3); j++) {
             old_pt = Array[j+FROM][k];
                   new_pt = Array[j+FROM+3][k];

    /* getting rid of cliff jump -----------------
     if (Array[j+FROM+3][k] - 100 > Array[j+FROM+2][k]) {
     mn_str = ((mn_str * 3) + Array [j + FROM + 4][k] -
                  old_pt) / 3;
```

```
          }
      else if (j+FROM > 0 && old_pt - 100 > Array [j - 1 +
                  FROM][k]) {
       mn_str = ((mn_str * 3) + new_pt - Array [j + FROM
                  + 1][k]) / 3;
            }
      else if ----------------------------  */
      mn_str = max (((mn_str * 3) + new_pt - old_pt)/3, 0);
smth[j+2] = (int) mn_str;
      }
      smth[j+2] = smth[j+1];
      smth[j+3] = smth[j+1];

      for (j = 0; j < POINTS; j++) {
            POWER[j][k] = smth[j];
            }
      }
}

/* -- picking peaks and placing thresholds ---- */
void pick_peak (k, cv2_pt)
 int k, cv2_pt;
{

/* Peak is taken as centered above threshold between threshold crosses up
and down. Defaults: Threshold is set to start at 1/10 value    of the
maximum peak, for monosyllables. Slope varies with threshold factor
(TFACTOR) chosen. Default is 0.0. If default is not used, slopes tend
toward a common endpoint, but do not achieve it within 8 secs (the time
for breath group). Each analysis starts at file start and goes to file end
(defaults). Smoothing prevents bias in peak placement by consonant
release energy. Peak location is at vowel peak energy. Location of peaks
is stored in A[][], which treats the first POWER index it looks at (from)
as zero, no matter what it is. First 40 values for other data, chnnl 0 (1
here), A[0][2], last 40, chnnl 1 (2 here), A[40][2] for speech data.    */
```

```
/* Note: noise is gated on as light beam is broken. Light beam is broken
once on each excursion upwards and again on excursion downwards.
Endpoint of excursion is considered to be the event of interest. It is taken
to occur halfway between two light beam breaks. In order to know which
pair of peaks encloses the up excursion peak, it is important to set the
light and sensor far from the midway point of the excursion. */

 int oldflag, b, newflag, lastx, x, y, j, c, p, loc, pk, t,          start,
length, t_start, t_end, ipi1, ipi2;
 char string[20];

   /* index to arrays = k=0 for chn 1 (other), k=1 for chn          2
(speech) */

      if (k EQ 1) {
            c = 40;
            }
      else {
            c = 0;
            }

      oldflag = 0;
      if (FLAG EQ 0) {
                  SLOPE0 = 0;     SLOPE = 0;      SLOPE1 = 0;
      }

      if (FLAG EQ 1 && k EQ 0) {
            TFACTOR = TFACTOR0;  MAX_PK = MAX_PK0;
            SLOPE = SLOPE0;
            }
      if (FLAG EQ 1 && k EQ 1) {
            TFACTOR = TFACTOR1;  MAX_PK = MAX_PK1;
            SLOPE = SLOPE1;
            }

      if (FLAG EQ 0) {
```

```
                start = FROM;
                length = POINTS;
        }
        else {
                start = STBG;    /* start of breath group */
                length = BGP;
        }

        t_start = max (start, FROM);
        t_end = min (length, POINTS);

        for (j = t_start; j < t_end + t_start; j++) {
/*      if (POWER[j][k] > dec(j) && dec(j) > 1) newflag = 1;
*/
      if (POWER[j][k] > TFACTOR) newflag = 1;
        else newflag = 0;
        if (oldflag != newflag) {
                A[c][oldflag] = j;
                if (oldflag == 1) {
                        A[c][oldflag] = j - 1;
                        c++;
                 }
                 oldflag = newflag;
           }
       } /* end for loop */

       if (newflag == 1) {
                A[c][1] = start + (length - 1);
                c++;
         }
       if (k EQ 0) {
                for (j = c; j < 40; j++) {
                        A[j][0] = 0;
                        A[j][1] = 0;
                        }
                }
```

```
        else {
             for (j = c; j < 80; j++) {
                  A[j][0] = 0;
                  A[j][1] = 0;
                  }
             }
/* -- plot threshold for breathgroup ---------- */

       lastx = t_start * XSCALE;
/*     t = dec (t_start)/cv2_pt;
*/     t = TFACTOR/cv2_pt;
       if (k EQ 1) y = 170;  /* speech [j][1] plots top screen */
     else y = 340;
       t_end = min(FROM + POINTS, start + length);
       for (j = t_start; j < t_end; j++)  {
             x = j * XSCALE;
/*           line (lastx, y - t, x, y - (dec(j)/cv2_pt), 1);
             t = dec (j)/ cv2_pt;
*/
             line (lastx, y - t, x, y - (TFACTOR/cv2_pt), 1);
             t = TFACTOR/ cv2_pt;
             lastx = x;
       }
/* ----- plot peak locations ---------------------*/
/* First and last peak not plotted if beyond Threshold at data start or end.
Peaks are taken to occur halfway between time of rise above threshold
and fall beneath threshold for the stimulus, because random noise is gated
equally before and after the stimulus excursion; there isn't a peak in the
MEASURE of the stimulus. Each two stimulus peaks represents 1 cycle
of finger movement. For speech, the peak is plotted at the point of peak
intensity within the data above threshold. Where the peak would occur
halfway through a frame, it is treated as being half a frame late. If onset
at 40, offset at 45, plot is at 43, not 42. Peaks whose base is less than 60
msec (2 pts) not plotted as these probably represent energy peaks due to
stop consonants. Counting the inclusive ends means plotted peaks
represent at least 60 msec above thresh. energy. */
```

```
       if (k EQ 0 ) {
             c = 0;
             }
       else {
             c = 40;
             }

    for (j = 0; j < 40; j++) {
/*           t = dec(A[c][0] + ((1  + A[c][1]-A[c][0]) /2));
*/
             t = TFACTOR;
         if (A[c][0] > 0 && A[c][1] != FROM + (POINTS - 1)
                 && A[c][1] - A[c][0] > 1 && t > 0)
                   {
                 if (k EQ 1)
                         {
                         loc = A[c][0];
                         pk = POWER[loc][k];
                   for (p = 0; p < (A[c][1]- A[c][0])+1; p++) {
                         loc = A[c][0] + p;
                         pk = max (pk, POWER[loc][k]);
                         if (pk EQ POWER[loc][k])  A[c][2]=
                              A[c][0] + p;
                               }
                         if (A[c][2] < (start + length))
                               {
                         x = (int) ((A[c][2] - FROM) * XSCALE);
                   line (x, y - 140, x, y- (t /cv2_pt), 1);
                               }
                         }
              else {
                         A[c][2] = A[c][0] + ((int) (1 + A[c][1]-
                                      A[c][0]) / 2);
                         }
                   }
             else {
```

```
                A[c][2] = 0;
                }
           c++;
         }
/* flatten the non-speech peaks, which are an artifact of the noise gate.
The solenoid follows a square wave. Find midpoint between peaks =
endpoints of excursion. PEAK_UP should never = 1 for the arm. */

     if (k EQ 0) {
           ipi1 = A[1][2] - A[0][2];
                 /* interpeak interval 1 */
           ipi2 = A[2][2] - A[1][2];
           if (ipi2 > 0) {
                 if ((PEAK_UP < 1 && ipi2 >= ipi1) ||
                     (PEAK_UP > 0 && ipi1 > ipi2))
/*   default: PEAK_UP = 0, and ipi2 > ipi1
     and first pair encloses down */
                     {
              A[0][3] = (ipi1 / 2) + A[0][2];
/* 1st true peak (top of cycle) */
/* remaining top of cycle peaks: */
                for (j = 1; j < c/2; j++) {
                     if (A[(j*2)+1][2] > 0) {
   A[j][3] = A[j*2][2] + ((A[(j*2)+1][2] - A[j*2][2]) / 2);
                     }
                     else A[j][3] = 0;
                     }
                }
           else {    /* first pair encloses up */
                     if ((PEAK_UP < 1 && ipi1 > ipi2) ||
                         (PEAK_UP > 0 && ipi2 > ipi1))
                         {
                     A[0][3] = (ipi2 / 2) + A[1][2];
                     for (j = 1; j < c/2; j++) {
                         if (A[(j*2)+2][2] > 0) {
A[j][3] = A[(j*2)+1][2]+((A[(j*2)+2][2]-A[(j*2)+1][2]) / 2);
```

```
                              }
                         else A[j][3] = 0;
                         }
                     }
                      }
               for (b = j; b < c; b++) {
                   A[b][3] = 0; /*zero remaining peaks */
                   }

/* spike for the non-speech peaks. The finger follows a sine wave
approximately but I am representing one point of its cycle only. */
                     }
               else {
                     for (j = 0; j < 80; j++) {
                           A[j][3] = 0;
                           }
                     }
               c = 0;
               for (j = 0; j < 40; j++) {
/*       t = dec(A[c][0] + ((1 + A[c][1]-A[c][0]) /2));
*/
                     t = TFACTOR;
                     if (A[c][0] > 0 && A[c][1] != FROM +
      (POINTS - 1) && A[c][1] - A[c][0] > 1 && t > 0)
                          {
                          x = (int) ((A[c][3] - FROM) * XSCALE);
                          if (A[c][3] < (start + length)) {
                          line (x, y - 140, x, y - (t
                                      /cv2_pt),     1);
                                }
                          }
                   c++;
                   }
             /* zero peak matrix outside the breathgroup */
             for (j = 0; j < 40; j++) {
                   if (A[j][3] < STBG || A[j][3] > (STBG + BGP))
```

```
                    {
                            A[j][3] = 0;
                    }
            }

    }
}
/* -------- send power contour to plotter ------------- */
void send_env (chn)
      int chn;
/* chn 2 = speech; 1 = other. Plot on screen is reproduced on paper,
except the padding to make 10 horizontal divisions on screen is foregone
on the plot (1/5 padding). POINTS = range of horizontal values in
screen points. msec = range of horizontal values in plotter values */
{
      int j, k, c, rf, t, pk, loc, p, thr, ipi1, ipi2, b;
      float ms_pt;
      double cv2, x, y, start, msec;
      char string[60], xlabel[10], ylabel[10];

      FILE * unit;
      unit = fopen ("COM2", "wb");
      TekInit (unit, 'D');
      TekCharSize (0.18, 0.30);
      TekFxd (0, 0);

      if (chn EQ 2) k = 1;
      else k = 0;    /* k links index of POWER to chnnl */

      ms_pt = 30.0;
/* timers 2 and 3 set SWEEP rate at 33.3 Hz = 30 msec*/
      start = FROM * ms_pt;
    msec = POINTS * ms_pt;

/* reduction factor rf decreases the range plotted. It  corresponds to the
screen power plot labels factor. */
```

```
      if (ADIV == 5) rf = 32;
      if (ADIV == 4) rf = 16;
      if (ADIV == 3) rf = 12;
      if (ADIV == 2) rf = 8;
      if (ADIV == 1) rf = 4;
      if (ADIV == 0) rf = 2;

    cv2 = 160 * rf;

/* mv2 produces too large numbers, so cv2 used. POWER includes a
division by cv/A_D units BEFORE the square. Only factor needed to
convert screen labels to plotter range is rf.
        POWER: (A-D units * cv/A-D units) **2 = cv2
*/

      if (k == 0) TekWindow (0.50, 9.50, 0.50, 3.50);
      if (k == 1) TekWindow (0.50, 9.50, 4.50, 7.50);

/* plots 2 windows, 1 per chnl on 8.5" * 11" paper. Place long side of
paper along BOTTOM of tablet, short side 0.5" to right of tablet's left
margin (plotter refuses to do labels if 0.0 = specified left margin.).*/

      TekScale (start, (double) start + msec, 0.00, cv2);
      TekLAxes (-(double)msec/8.00, (double)cv2/4.00,
            (double)start, 0.00);
      TekMove ((double) start, 0.00);

    if (k EQ 0) {
            SLOPE = 0;             MAX_PK = MAX_PK0;
            TFACTOR = TFACTOR0;
            }
      else {
            SLOPE = SLOPE1;          MAX_PK = MAX_PK1;
            TFACTOR = TFACTOR1;
            }
```

```
/* ---------- data plot loop ---- */

      for (j = 0; j < POINTS; j++) {
            x = start + (j * ms_pt);
          if (k EQ 0) {
                  if (POWER[j][k] > 0) y = MAX_PK;
                  else y = 0;
          }
            else y =  POWER[j+FROM][k];
            TekDraw (x, y);
      }
/* --------- threshold plot ------- */

      thr = max (0, (BGP + STBG) - FROM);
      thr = min (POINTS, thr);

/*    TekMove ((double) start, (double) dec(0));
      for (j = 0; j < thr + 1; j++) {
            x = start + (j * ms_pt);
            y = dec (j + FROM);
            TekDraw (x, y);
            }

      TekMove ((double) start, (double) dec(0));
      TekMove ((double) start, (double) TFACTOR);
      sprintf (string, "%5.3f", (int) TFACTOR);
      TekLbOrg (1);
      TekLabel (string);
*/
/* --------- plot peak locations -----*/
/* same rules for peak picking here as in pick_peak */

      if (k EQ 0 ) {
            c = 0;
            }
      else {
```

```
        c = 40;
        }

for (y = 0; y < 40; y++) {
        t = TFACTOR;
    if (A[c][0] > 0 && A[c][1] != FROM + (POINTS - 1)
        && A[c][1] - A[c][0] > 1 && t > 0)
            {
            if (k EQ 1)
              {
                    loc = A[c][0];
                    pk = POWER[loc][k];
        for (p = 0; p < (A[c][1]- A[c][0])+1; p++) {
                          loc = A[c][0] + p;
                          pk = max (pk, POWER[loc][k]);
              if (pk EQ POWER[loc][k]) A[c][2]= A[c][0] +p;
                          }
                    x = ms_pt * A[c][2];
                    }
            else {
                    x = (ms_pt * (A[c][0] + ((int) (1 +
                          A[c][1] - A[c][0]) / 2)));
                    }
              if (k EQ 1) {
                    if (A[c][2] < (thr+FROM) && A[c][2] > 0)
                          {
                          TekMove (x, (double)j);
        TekDraw (x, (double) (cv2 - (cv2 / 8)));
                          sprintf (string, "%d", (int) x);
        TekMove ((double) x, (double) (cv2 - (cv2 / 4)));
                          TekLbDir (90.00);
                          TekLabel (string);
                          }
                    }
        }
        c++;
```

```
            }

/* find midpoint between peaks = endpoints of excursion. */

    if (k EQ 0) {
            ipi1 = A[1][2] - A[0][2];
                    /* interpeak interval 1 */
            ipi2 = A[2][2] - A[1][2];
            if (ipi2 > 0) {
                            if ((PEAK_UP < 1 && ipi2 >= ipi1) ||
                                    (PEAK_UP > 0 && ipi1 > ipi2))
                                    {
                            A[0][3] = (ipi1 / 2) + A[0][2];
    /* 1st true peak (top of cycle) */
    /* remaining top of cycle peaks: */
                            for (j = 1; j < c/2; j++) {
                            if (A[(j*2)+1][2] > 0) {
A[j][3] = A[j*2][2] + ((A[(j*2)+1][2] - A[j*2][2]) / 2);
                            }
                            else A[j][3] = 0;
                            }
                }
            }
            else {          /* first pair encloses up */
                            if ((PEAK_UP < 1 && ipi1 > ipi2) ||
                                    (PEAK_UP > 0 && ipi2 > ipi1))
                                    {
                            A[0][3] = (ipi2 / 2) + A[1][2];
                            for (j = 1; j < c/2; j++) {
                                if (A[(j*2)+2][2] > 0) {
A[j][3] = A[(j*2)+1][2]+((A[(j*2)+2][2]-A[(j*2)+1][2]) / 2);
                                }
                                else A[j][3] = 0;
                             }
                        }
                            }
```

```
            for (b = j; b < c; b++) {
                A[b][3] = 0; /* zero remaining peaks */
                }

/* spike for the non-speech peaks. The finger follows a sine wave
approximately but I am representing one point of its cycle only. */
                }
        else {
                for (j = 0; j < 80; j++) {
                        A[j][3] = 0;
                        }
                }
        c = 0;
        for (j = 0; j < 40; j++) {
                t = TFACTOR;
                if (A[c][0]> 0 && A[c][1] != FROM +(POINTS-1)
            && A[c][1] - A[c][0] > 1 && t > 0)
                {
                        x = ms_pt * A[c][3];
        if (A[c][3] < (thr + FROM) && A[c][3] > 0) {
                                TekMove (x, (double)j);
        TekDraw (x, (double) (cv2 - (cv2 / 8)));
                                sprintf (string, "%d", (int) x);
        TekMove ((double) x, (double) (cv2 - (cv2 / 4)));
                                TekLbDir (90.00);
                                TekLabel (string);
                                }
                        }
                c++;
                }

        TekLbDir (0.00);

    /* LbOrg Matrix 7 4 1
      origin: 5.   8 5 2
               9 6 3 */
```

```
/* \x0b moves the label plot up twice the char height. \x0a = move plot
down. \x0b = move plot up. \x08 = move plot left \x07 beep to signal
finish */

            sprintf (xlabel, "\x0a\x0a msec");
            TekMove ((double) (msec/16.00) + start, 0.00);
            TekLbOrg (4);
            TekLabel (xlabel);
            sprintf (ylabel, "\x08\x08cv");
            TekMove (start, (double) 0.63 * cv2);
            TekLbOrg (5);
            TekLabel (ylabel);
            TekCharSize (0.15, 0.25);
            sprintf (ylabel, "\x082");
            TekMove (start, (double) 0.63 * cv2);
            TekLbOrg (7);
            TekLabel (ylabel);
            sprintf (ylabel, "\x07");
            TekLabel (ylabel);
            fflush (unit);
            }

/* -- plot the envelope; second-level function -------- */
void plot_env (total, page, cv2_pt)
      int total, page, cv2_pt;
/* points in array, which page to plot, (RAW) counts per pixel, points
per horizontal pixel. time (x axis) vs power (y axis). */
{
      int lastx, lasty0, lasty1, pps, start, length;
      int pages, pix_div, width, to, x, y, j, k, chn, c;
      float ms_div, cv2_div;
      char string[40];

      pps = WLIST[W] * total / 32; /* nb 1/32 = 512/16K */
    if (total<2 || pps<2) {
            putch(7);
```

```
          return;
          }

     pages = (long) (total + pps - 1L) / pps;
     page = min (page, pages-1);
     FROM = page * pps;
     to   = min (FROM+pps-1, total-1);
     POINTS = to - FROM + 1;
     pix_div = 512/(10 * pages);
     ms_div = (float) (15360/SWEEPS) * (float) pix_div;
/* convert points to ms per div = time/pt (30 msec) * 512 pts *
(pt/div)/pages. Values here are approximate due to imprecision in page,
pages. Precise values are printed on the paper plots (with send_env) */

     if (POINTS<2) {
          putch(7);
          return;
          }

     cv2_pt = max (cv2_pt, 1);

/* cv2 per pt here will not be the square of cv_pt for raw data as in
small.c because AMPL, and therefore POWER, are measures of mean
power or amplitude, and don't necessarily
reflect the maximum raw values which attract attention on
the raw plots. Usual: 80 cv/div on raw -> 320 cv2/div on power plots.
     No conversion from A-D units to cv2 required for label.
It occurs before data square. cv2_pt * 40 screen pts/div = cv2/div */
     cv2_div = (float) cv2_pt * 40;

/* Calibration with oscilloscope: 0.2 Volts=160 counts = 1V/800 counts
vertical. V/div = cpp * 40/800. Volts are too large a unit (require
floats), mv too small, so work in centivolts. 1cv/8 counts. */

/* smooth data to identify more clearly main peaks and to isolate energy
due to vowel (AMPL) and discount energy due to stop C release. smooth
```

```
for points, starting at from. */

/* CALC flags whether the data have already been smoothed (ie come
from datafile). Smoothing puts data in the first channel into array [j][0]
and data in second channel (speech) into array [j][1]. */

     if (CALC EQ 0) {
          smooth(AMPL);
          smooth(POWER, 0);
          for (k = 0; k < 2; k++) {
                    for (j = 0; j < POINTS; j++) {
                    POWER[j][k] = (int)(sqr((float)
                     POWER[j][k] /8));
                         }
                    }
               CALC = 2;
               }

/* set up for plot start. Both channels plot on screen automatically ch 2
plots in upper half of screen, ch 1 in lower half. chn = k+1 */

          XSCALE = 512.00 / pps;
          memcpy (PAGE0, GRID, 32768);
          for (k = 0; k < 2; k++) {
          lastx = 0;
               MAX_PK = 0;    /* was if (FLAG EQ 0 */
   lasty0 = (int)((float) POWER[FROM][k]/ cv2_pt);
               if (k EQ 1) {
                    c = 170;
/* speech [j][1] plots top screen */
                    }
               else {
                    c = 340;          /* [j][0] plots below */
                    }
/* ----data plot, both channels------------------- */
/* Selection of maximum. As threshold is calculated based on the
```

```
maximum in the section of data being plotted, it may have a lower value
over a subsection compared to its value over the whole file (max
POWER/3). */

                      start = max( FROM, STBG);
                      length = min( BGP, POINTS);

                      if (k EQ 1) {
                              for (j = 0; j < (POINTS - 1); j++)  {
        y = (int)((float) POWER[j+FROM][k]/ cv2_pt);
                                      x = j  * XSCALE;
                                      line (lastx, c-lasty0, x, c-y, 1);
                                             if (FLAG EQ 0) {
                                                     MAX_PK = max (y,
MAX_PK);
                                                     }
                                             else {
        if (j >= start && j <= start + length)
                                                             {
        MAX_PK = max (y, MAX_PK);
                                                             }
                                                     }
                                             lasty0 = y;
                                             lastx = x;
                                             }
                                      }
                              else {
                                      for (j = 0; j < (POINTS-1); j++)
                                             {
     y = (int)((float)POWER[j+FROM][k] / cv2_pt);
  /* identify */                      if (FLAG EQ 0) {
  /* MAX_PK    */                             MAX_PK = max (y,
MAX_PK);
                                                     }
                                             else {
        if (j >= start && j <= start + length)
```

```
                                        {
      MAX_PK = max (y, MAX_PK);
                                        }
                                   }
                              }
                         for (j = 0; j < (POINTS - 1); j++)
                              {
                              if (POWER[j+FROM][k] < = 1) {
/* eliminates random noise effects */
                                   y = 0;
                                   }
                              else {
                              y = MAX_PK;
                                   }
                              x = j  * XSCALE;
     line (lastx, c - lasty0, x, c - y, 1);
                              lasty0 = y;
                              lastx = x;
                              }
                         }

/*          if (k EQ 0) {
              Ggoto_xy (3, 70);
               sprintf (string, "%3d", FROM);
               gtext (string);
                }
          else {
               Ggoto_xy (5, 72);
               sprintf (string, "%3d", POINTS);
               gtext (string);
               }
*/
                    if (FLAG EQ 0)  {
                         MAX_PK = MAX_PK * cv2_pt;
                         }
                    if (FLAG EQ 0 && k EQ 0) {
```

```
                            MAX_PK0 = MAX_PK;
                            TFACTOR0 =TFACTOR;
                            }
                      if (FLAG EQ 0 && k EQ 1) {
                            MAX_PK1 = MAX_PK;
                            TFACTOR1 = TFACTOR;
                            }
                      pick_peak (k, cv2_pt);
                      }
/*   Ggoto_xy (7, 73);
    sprintf (string, "%5d", dec(0));
    gtext (string);
*/
                Ggoto_xy (9, 73);
                sprintf (string, "%5.3f", TFACTOR1);
                gtext (string);

                Ggoto_xy (11, 73);
                sprintf (string, "%5.3lf", SLOPE1);
                gtext (string);

                Ggoto_xy (13, 73);
                sprintf (string, "%4d", length);
                gtext (string);

                Ggoto_xy (17, 70);
                sprintf (string, "%3d", page + 1);
                gtext (string);

                Ggoto_xy (17, 77);
                sprintf (string, "%3d", pages);
                gtext (string);

                Ggoto_xy (19, 72);
                sprintf (string, "%9.2f", cv2_div);
                gtext (string);
```

```
/*cv_div = cv2_div */

                Ggoto_xy (21, 72);
                sprintf (string, "%7.2f", ms_div/30.00);
                gtext (string);
                }

/* ---- show the envelope; calls above routine ---------- */
void show_env ()
{
     static int amp[6]= {2, 4, 8, 12, 16, 32};
       /* old {1, 1, 2, 4, 8, 16} */
     static int page = 0;
     int total, pages, chn;
     char ch;

     total = SWEEPS;
     pages = (long) (total + WLIST[W] - 1L) / WLIST[W];

     cls();
     printf ("\n\n\n");
printf ("Plot of envelope data. The key list is:     \n\n");
     printf ("   w, n    wider, narrower window.   \n");
     printf ("   l, r    page left, page right.    \n");
     printf ("   +, -    increase, decrease signal  \n");
printf ("   s      send speech envelope to plotter  \n");
printf ("   o      send other envelope to plotter   \n");
     printf ("   Esc     quit.  \n\n");

/*   printf ("Current FILENAME: %s\n\n", FILENAME);
     printf ("New FILENAME for paper plot ?\n");
     printf ("Hit Enter if NO, any other key if yes.\n\n");
     kb_flush();
     if (getch() != '\r') {
          kb_flush();
          printf ("Type FILENAME.\n\n");
```

```
                gets(FILENAME);
        }
*/
        graf_mode();
        graf_cls();
        make_grid();
        memcpy (GRID, PAGE0, 32768);
        plot_env (total, page, amp[ADIV]);
        while ( (ch = getch()) != 27 ) {
                switch (ch) {
                        case 'n':
                        case 'N':
                                if (W < 1) { putch(7); break; }
                                W--;
                                pages = (long) (total + WLIST[W] - 1L)
                                                / WLIST[W];
                                page = min (page, pages-1);
                                plot_env (total, page, amp[ADIV]);
                                break;
                        case 'w':
                        case 'W':
                                if (W > 4) { putch(7); break; }
                                W++;
                                pages = (long) (total + WLIST[W] - 1L)
                                                / WLIST[W];
                                page = min (page, pages-1);
                                plot_env (total, page, amp[ADIV]);
                                break;
                        case 'r':
                        case 'R':
                                if (page > pages-2) { putch(7); break; }
                                page++;
                                plot_env (total, page, amp[ADIV]);
                                break;
                        case 'l':
                        case 'L':
```

```
                    if (page < 1) { putch(7); break; }
                    page--;
                    plot_env (total, page, amp[ADIV]);
                    break;
               case '+':
               case '=':
                    if (ADIV < 1) { putch(7); break; }
                    ADIV--;
                    plot_env (total, page, amp[ADIV]);
                    break;
               case '-':
               case '_':
                    if (ADIV > 4) { putch(7); break; }
                    ADIV++;
                    plot_env (total, page, amp[ADIV]);
                    break;
               case 's':
               case 'S':
                    chn = 2;
                    send_env (chn);
                    break;
               case 'o':
               case 'O':
                    chn = 1;
                    send_env (chn);
                    break;
               default:
                    putch (7);
          } /* end switch */
     } /* end while */

     kb_flush();
     text_mode();
}

/* -----------write contour to external file --------- */
```

```
save_POWER ()
{
        FILE * unit;
        int result;
        char c;

        /* POWER saved as basis for data analysis. AMPL
           can be printed with small.c
        */

        result = access(INTFILE,0);
        if (result!= FAILURE) {

        printf ("File already exists.\n");
        printf ("Use the filename anyway ? \n");
        c= getch();
        if (c!= 'y' && c!= 'Y') return (FAILURE);
        }

        if ((unit = fopen(INTFILE, "wb"))==NULL) {
        printf ("Can't open the file.\n");
        return (FAILURE);
        }
        else {
                fwrite((char far *) &BUFLEN, 2, 1, unit);
                fwrite((char far *) &TDIV, 2, 1, unit);
                fwrite((char far *) POWER, sizeof(int), (SWEEPS *
                                2), unit);
                fclose(unit);
                return(SUCCESS):
                }
        }
/* -----------write peaks to external file --------- */
save_peaks ()
{
        FILE * unit;
```

```
        int result, j, b, tf0, tf1;
        char c, peakfile[15];

/* A[][] saved as basis for data analysis. Recommend using filename
which associates peak file with POWER source  */

        b = 0;
        printf ("Filename (end in .pk) ?\n");
        kb_flush ();
        gets(peakfile);
        result = access(peakfile,0);
        if (result!= FAILURE) {
                printf ("File already exists.\n");
                printf ("Use the filename anyway ? \n");
                c= getch();
                if (c!= 'y' && c!= 'Y') return (FAILURE);
                }

        if ((unit = fopen(peakfile, "wb"))==NULL) {
                printf ("Can't open the file.\n");
                return (FAILURE);
                }
        else {

                tf1 = (int) (TFACTOR1);
                fwrite((char far *) &PEAK_UP, 2, 1, unit);
                fwrite((char far *) &tf1, 2, 1, unit);
                fwrite((char far *) &STBG, 2, 1, unit);
                fwrite((char far *) &BGP, 2, 1, unit);
                for (j = 0; j < 40; j++) {
                        if (A[j][3] > 0) {
                                putw(A[j][3], unit);
                                b++;
                                }
                        }
                for (j = b; j < 40; j++) putw(0, unit);
```

```
        /* filling in blanks in stimulus matrix  */

        b = 0;
        for (j = 40; j < 80; j++) {
            if (A[j][2] > 0) {
                putw(A[j][2], unit);
                b++;
                }
            }
        for (j = b; j < 40; j++) putw(0, unit);
        fclose(unit);
/*  printf("TFACTOR0: %6.2f       TFACTOR1: %6.2f\n",
TFACTOR0,     TFACTOR1);
    printf("SLOPE1: %6.4lf\n", SLOPE1);      */

        return(SUCCESS);
        }
    }
/* ---------- load data from file ---------- */
read_POWER ()
{
    int result;
    FILE * unit;
    if((unit = fopen(FILENAME, "rb"))==NULL) {
        printf("Can't open file. \n");
        return(FAILURE);
    }
    result = fread ( (char far *) &BUFLEN, sizeof(int), 1,
        unit);
    if (result != 1)
        printf ("Error reading BUFLEN.\n\n");

    result = fread ( (char far *) &TDIV,  sizeof(int), 1,
        unit);
    if (result != 1) printf ("Error reading TDIV.\n\n");
  if (fread((char far *) POWER, sizeof(int), SWEEPS * 2,
```

```
            unit)!= 1) {
                    if (feof(unit)!= 1);
                    printf("File read. \n");
                    CALC = 1;
                    FLAG = 0;
                    }
          else {
                  printf("Error reading file.\n\n");
              }
      fclose(unit);
    printf("BUFLEN %d, TDIV %d\n", BUFLEN, TDIV);
}
/* ----- send contour to printer ---- */
void print_POWER ()
{
int j, c, sum, b;
char ch, input[4];
float freq;

printf ("Print Power and Amplitude data (y)");
printf (" or Peak Location data (n) ?\n");
kb_flush();
if (getch() EQ 'y') {
      printf ("Press ENTER to start.\n\n");
      kb_flush();
      do { } while (getch() != '\r');
      if (CALC EQ 1)
printf ("Ampl. (pre-smooth) values are invalid\n\n");
/* Speech = chn 2 and Other = chn1 */
printf ("      Other    Speech            Other     ");
printf (" Speech\n");
printf ("      Amp  Power  Amp  Power ");
printf ("      Amp  Power  Amp  Power\n");
printf ("Index. S[0]  I[0]  S[1]  I[1] ");
printf ("Index. S[0]  I[0]  S[1]  I[1]\n");
for (j = 0; j < (SWEEPS/2); j++) {
```

```
    printf ("%4d. %4d  %4d  %4d  %4d  ", j, AMPL[j][0],
              POWER[j][0],AMPL[j][1], POWER[j][1]);
    printf ("%4d. %4d  %4d  %4d  %4d\n", j+(SWEEPS/2),
         AMPL[j+(SWEEPS/2)][0], POWER[j+(SWEEPS/2)][0],
              AMPL[j+(SWEEPS/2)][1], POWER[j+(SWEEPS/2)][1]);
    }
}
else {
      MAX_PK = MAX_PK1; TFACTOR = TFACTOR1; SLOPE =
SLOPE1;
/*     printf ("\nSpeech Start Threshold: %5d\n\n", dec (0));
*/
printf ("\nSpeech Start Threshold: %5.3f\n\n", TFACTOR);
printf ("Speech peaks\n");
printf ("Index  Start  End  Diff  Diff (ms) ");
printf (" Plot Period \n");
c = 0;
j = 40;
/* for j =40 */
if (A[j][1] - A[j][0] != 0 ) {
    printf ("%3d. %5d  %5d %3d  %7.2f        %3d\n", j,
             A[j][0], A[j][1], (1 + A[j][1]-A[j][0]), (float)(1          +
A[j][1] - A[j][0]) *(15360/SWEEPS), A[j][2]);
             }
      for (j = 41; j < 80; j++) {
             if (A[j][1] - A[j][0] != 0 ) {
    printf ("%3d. %5d  %5d %3d  %7.2f       %3d %4d\n", j,
             A[j][0], A[j][1], (1 + A[j][1]-A[j][0]), (float)(1          +
A[j][1] - A[j][0])*(15360/SWEEPS), A[j][2],              A[j][2]-A[j-1][2]);
                    c++;
                    }
             }
/* check for extraneous second peak before save */
    for (j = 41; j < 80; j++) {
             if (A[j][3] < A[j-1][3] && A[j][3] != 0) {
      printf ("Delete extra peak A[%2d][3]: %3d (y/n)\n",
```

```
                    j, A[j][3]);
                    kb_flush ();
                    if (getch() EQ 'y' || getch() EQ 'Y') {
                         A[j][3] = 0;
                         printf ("A[%2d][3]: %3d\n", j, A[j][3]);
                         }
                    }
               }
/*--------frequency calculation---------------*/

     j = 40 + c; /* index */
     sum = 0;  b = 0;
     for (c = j; c > 40; c--) {
          if (A[c][2] > 0) {
               sum = A[c][2] - A[c-1][2] + sum;
               b++;
          }
     }

     if (b > 1) {
          freq =     33.3 / ((float) (sum) / b);
printf ("\nFrequency of speech:");
printf (" %4.2f over %2d interpeak intervals\n", freq, b);
/* 1000 ms / (average pts * 30 ms_pt) */
          }
else {
     printf ("\nToo few peaks to calculate a");
     printf(" frequency\n");
     }
printf ("\nPress ENTER to print arm data.\n\n");
kb_flush();
do { } while (getch() != '\r');

/* The extra 1 in printf, parameter 4, is due to inclusion of both ends of
the contour above threshold. sampling period between buffer averages
(ms) = total record time (15.36 secs) / # SWEEPS (512 points) = 30
```

```
ms/pt of power data */

MAX_PK = MAX_PK0;      TFACTOR = TFACTOR0;   SLOPE =
0;
printf ("\nArm Threshold: %5.3f\n\n", TFACTOR);
/*   printf ("\nArm Threshold: %5d\n\n", dec(0));
*/
printf ("Arm peaks\n");
printf ("Index  Start  End  Diff  Diff (ms)  Peak  Plot");
printf (" Period\n");
c = 0;
     for (j = 0; j < 40; j++) {
          if (A[j][1] - A[j][0] != 0 ) {
printf ("%3d. %5d  %5d %3d  %7.2f      %3d", j, A[j][0],
   A[j][1], (1 + A[j][1]-A[j][0]), (float)(1 + A[j][1] -
     A[j][0]) *(15360/SWEEPS), A[j][2]);
                if (fmod(j,2) EQ 0) {
                     printf ("\n");
                     }
                else {
                     printf ("%5d", A[j-(c+1)][3]);
                     b = j -(c+1);
                     if (c > 0 && A[b][3] > 0) {
          printf ("   %4d\n", A[b][3] - A[b-1][3]);
                          }
                     else printf ("\n");
                c++;
                }
          }
    }
  /* check for extraneous second peak before save */
for (j = 1; j < 40; j++) {
   if (A[j][3] < A[j-1][3] && A[j][3] != 0) {
printf ("Delete extra peak A[%2d][3]: %3d (y/n)\n",
          j, A[j][3]);
          kb_flush ();
```

```
            if (getch() EQ 'y' || getch() EQ 'Y') {
                  A[j][3] = 0;
                  printf ("A[%2d][3]: %3d\n", j, A[j][3]);
                  }
            }
      }
      /*-------- frequency calc ----------*/
j = c; /* index */
sum = 0;   b = 0;
for (c = j - 1; c > 0; c--) {
      if (A[c][3] > 0) {
            sum = A[c][3] - A[c-1][3] + sum;
            b++;
            }
      }

if (b > 1) {
      freq =        33.3 / ((float) (sum) / b);
printf ("\nFrequency of arm:");
printf (" %4.2f over %2d interpeak intervals\n", freq, b);
/* 1000 ms / (average pts * 30 ms_pt) */
      }
else printf ("\nToo few peaks to calculate a frequency\n");
printf ("\nPeaks picked ONLY for data and threshold");
printf (" visible after E\n");
}
}
/* ---------------- breathgroup ----- */
int breath()
{
int last, oldflag, count, zflag, j;

zflag = 0;
oldflag = 1;
count = 0;
for (j = 1; j < 512; j++) {
```

```
        if (POWER[j][1] EQ 0) zflag = 0;
        else zflag = 1;
        if (oldflag != zflag) {
                BR[count] = j - 1;
                count++;
                }
                oldflag = zflag;
        }
        last = count - 1;
        for (j = count; j < 60; j++) {
                BR[j] = 0;
                }               /* complete with zeros */

/* for (j = 1; j < 59; j += 2) {
        printf("%2d. Start BGP: %3d             Length BGP: %3d\n",
                j, BR[j], 1 + BR[j+1] - BR[j]);
        }
*/
        return(last);
}
/* --------- change parameter values ------------- */
void fixit()
{
int j, k, last;
char x, ch, c, str[10], tf[10], sl[10];

for (;;)
        {
        printf("\n\n                        MENU\n");
/*printf("t TFACTOR\ns SLOPE\nb BREATHGROUP\nh HELP\nq
QUIT\n");   */

        printf("t TFACTOR\np PEAK UP\nb BREATHGROUP\nh");
        printf(" HELP\nx EXIT\n");
        kb_flush();
        switch (getch()) {
```

```
            case 'h':
            case 'H':
             printf("                    HELP\n\n"):
             printf("t:change the height at which\n");
printf(" the speech threshold starts. The default\n");
printf("  is 10% of MAX_PK (speech).\n\n");

/*    printf("s:change the slope of the\n");
     printf("  threshold decline.  The default is 0.\n\n");
*/
      printf ("p: choose peaks in narrow/wide gaps.\n\n");
             printf("b:change the start and length\n");
printf("  of the breathgroup.  The default is start\n");
printf("  at 0 and length of 511 points.\n\n");
             printf("h:help.  This message.\n");
                   break;
            case 't':
            case 'T':
                  printf("                  TFACTOR\n\n");
      printf("Current TFACTOR (speech): %5.2f\n", TFACTOR1);
      printf("Current MAX_PK (speech): %4d\n\n", MAX_PK1);
      printf("New TFACTOR (speech = s; other = o;");
                  printf(" default = d; no = n) ?");
                  c = getch();
                  printf("%c\n", c);
            if (c EQ 's' || c EQ 'S' || c EQ 'o' || c EQ 'O')
                         {
      printf("\nEnter a double format number (Ex: 3.3)\n\n");
                         gets(tf);
                         if (c EQ 's' || c EQ 'S') {
                               TFACTOR1 = atof(tf);
      printf("Tfactor1: %5.3f\n", TFACTOR1);
                               }
                         else {
                               TFACTOR0 = atof(tf);
      printf("Tfactor0: %5.3f\n", TFACTOR0);
```

```
                                        }
                                }
                        else if (c EQ 'd' || c EQ 'D') {
                                printf ("Set defaults (y/n) ?\n");
                                kb_flush();
                                x = getch();
                                if (x EQ 'y' || x EQ 'Y') {
                                        gets(tf);
                                        TFACTOR0 = atof(tf);
                                        TFACTOR1 = TFACTOR0;
                                        TFACTOR = TFACTOR0;
                                        }
                                else {
                                        TFACTOR1 = 10.0;
                                        TFACTOR0 = 10.0;
                                        }
        printf("Default Tfactor0: %5.3f instated\n", TFACTOR0);
        printf("Default Tfactor1: %5.3f instated\n", TFACTOR1);
                                }
                        break;
/*      case 's':
        case 'S':
                printf("                SLOPE\n\n");
                printf("Current SLOPE (speech): %4.2f\n", SLOPE1);
printf("New SLOPE (speech = s; other = o; default = d; no = n) ?");
                c = getch();
                printf("%c\n", c);
                if (c EQ 's' || c EQ 'S' || c EQ 'o' || c EQ 'O')
                        {
        printf("\nEnter a float format number (Ex: 1.2)\n");
                        gets(sl);
                        if (c EQ 's' || c EQ 'S') {
                                SLOPE1 = atof(sl);
                                printf("Slope1: %4.2f\n", SLOPE1);
                                }
                        else {
```

```
                                SLOPE0 = atof(sl);
                                printf("Slope0: %4.2f\n", SLOPE0);
                                }
                        }
                else if (c EQ 'd' || c EQ 'D') {
                        SLOPE0 = 0.00;
                        SLOPE1 = 0.00;
                        printf("Slope1: 0.00\n");
                        printf("Slope0: 0.00\n");
                        }
                break;
*/
        case 'p':
        case 'P':
printf ("Peaks must be picked at bottom of cycle.\n");
printf ("Type 'w' if peaks are being picked at top.\n");
if (PEAK_UP < 1) printf ("Currently: NARROW\n");
else printf ("Currently: WIDE\n");
                c = getch();
                if (c EQ 'w' || c EQ 'W') {
/*      PEAK_UP = 1;  */
printf ("Not possible to alter this value\n");
                        }
                else PEAK_UP = 0;
                break;
        case 'b':
        case 'B':
                printf("New BREATHGROUP (d = default;");
                printf(" s = speech; n = no)\n");
                c = getch();
                printf("%c\n", c);
                if (c != 'n' && c != 'N') {
                        if (c EQ 'D' || c EQ 'd') {
/*                      strcpy(str,"0");
*/

                                x EQ 'd';
```

```
      printf ("Default is all breathgroups\n");
                              STBG = 0;
                              BGP = 511;
                              }
                      else if (c EQ 's' || c EQ 'S') {
      printf("Current BGP start (speech): %3d\n", STBG);
      printf("Current BGP length (speech): %3d\n\n", BGP);
                              printf("              New BGP\n\n");
                              if (breath() > 0) last = breath();
                              if (fmod(last,2) != 0) last = last - 1;
/* printf("Start speech: POWER");
printf("[%3d]   End speech: POWER[%3d]\n\n",BR[1], BR[last]);
printf("Breathgroups, listed by power matrix index:\n");
printf("last BR index for speech: %3d\n", last);
      for (j = 1; j < last; j += 2) {
printf("%2d. Start BGP: %3d          Length BGP: %3d\n",
                              j, BR[j], 1 + BR[j+1] - BR[j]);
              }
*/
                              printf("Select a breathgroup\n");
/* printf("0: all BGPs (default)\n");
printf ("1 or more: index to single BGP\n");
*/

printf ("p: specify begin, endpoints of breathgroup\n");
                              kb_flush();
                              x = getch();
                          }   /* end else if */
                    if (x EQ 'p' || x EQ 'P')
                              {
      printf ("Start point ? Currently %3d\n\n", STBG);
printf ("Type ENTER to accept, any other key to change\n");
                              kb_flush();
                              if (getch() != '\r') {
                                   printf ("Type start point.\n\n");
                              kb_flush();
```

```
                              gets(sl);
                              STBG = atoi(sl);
                              }
      printf ("End point ? Currently %3d\n\n", STBG + BGP);
printf ("Type ENTER to accept, any other key to change\n");
                        kb_flush();
                        if (getch() != '\r') {
      printf ("Else type end point.\n\n");
                        kb_flush();
                              gets(tf);
                              BGP = atoi(tf) - STBG;
                              }
                  }
/*              else if (x EQ '0') {
                        STBG = BR[1];
                        BGP = BR[last] - BR[1];
                        j = x;
                  }
                  else if (x EQ 'd') {
                        STBG = 0;
                        BGP = 511;
                        j = 0;
                        }
                else {
                        j = atoi(str);
                        STBG = BR[(j * 2) - 1];
                        BGP = BR[j * 2] - STBG;
                  }
*/
                  }
printf("\nSelected: Start %3d  Length %3d\n\n", STBG, BGP);
            break;
      case 'x':
      case 'X':
            goto fixed;
            break;
```

```
      }                         /* end switch */
}
fixed: printf("End of fixing\n");
printf("\n          SUMMARY\n\n");
printf("Tfactor (speech): %5.3f\nTfactor (arm): %4.2f\n",
      TFACTOR1, TFACTOR0);
/*printf("Slope (speech): %5.3f\nSlope (arm): %4.2f\n",
      SLOPE1, SLOPE0);
*/

if (PEAK_UP < 1)
      printf("Peaks (arm) picked in narrow gaps\n");
else printf("Peaks (arm) WRONGLY picked in wide gaps\n");
printf("Breathgroup start: %3d", STBG);
printf("     Breathgroup length: %3d\n", BGP);

FLAG = 1;

}

/* ------------ HELP --------------- */
void help()
{
      printf ("\nYou can use these keys:\n\n");
      printf ("  T  alter TDIV parameter\n");
      printf ("  R  record sound        \n");
      printf ("  E  view envelope       \n");
      printf ("  S  plot speech power. Type E first. \n");
      printf ("  O  plot other power. Type E first. \n");
      printf ("  I  print power values. Type E first. \n");
      printf ("  W  write power data to disk \n");
      printf ("  P  write peak locations to disk \n");
      printf ("  D  get data from power file  \n");
      printf ("  Q  quit program        \n");
      printf ("  X  change threshold \n");
      printf ("  H  help; this message  \n\n");
```

```
}
/* ------------------------------------------ */
main ()
{
      static int channels[8] = {0,1,2,3,4,5,6,7};
/*    static int factors[6] = {1, 2, 4, 8, 16, 32}; */
      int result;
      char ch, input[4], filename[15];

      check_vector (0x66);          /* Is Labpac there */

      /* ---------- Introduction ---------- */
      cls();
printf ("\n\n\n Speech and two-bar light detector");
printf (" program.\n\n");
      printf (" DATE (dd-mm-yy) ?\n\n");
      gets(DATE);
      for (;;) {          /* forever */
            printf ("----Main loop----\n");
printf ("Choices: X T R D E W P Q I S O; H for help.\n");
            kb_flush();
            switch (getch()) {
                  case 'h':
                  case 'H':
                        printf ("Help.\n");
                        help ();
                        break;
                  case 'x':
                  case 'X':
                        printf ("Fix it ");
                        fixit ();
                        break;
                  case 'r':
                  case 'R':
                        printf ("Record for 15 secs.\n");
                        record ();
```

```
            break;
      case 'd':
      case 'D':
            printf ("Get data from file.\n");
            kb_flush();
            printf("Filename (14 chars max) ? \n"):
            gets(FILENAME);
            read_POWER();
            break;
case 'i':
      case 'I':
    printf ("Print power data.\n");
            print_POWER();
            break;
case 'p':
      case 'P':
              printf ("Save peaks.\n");
            save_peaks();
            break;
      case 'e':
      case 'E':
          show_env ();
            break;
      case 'w':
      case 'W':
            printf ("Write power data to disk.\n");
            kb_flush ();
            printf ("Filename (end in .int) ?\n");
            gets(INTFILE);
            save_POWER();
            break;
      case 'q':
      case 'Q':
            goto bottom;
            break;
} /* end switch */
```

```
        } /* end for */

bottom:
        printf ("Experiment over.\n\n");
        labpac (RESET);
/*      hfree ((char far *) pointer); */
        exit (0);
}
```

FREQ.C

```
/*Program reads peak locations from .pk files (output of sol, solfin, spl,
twobar.c), computes period, standard deviation, and n. for other (chnnl
0) and speech (chnnl 1) converts period data to proportions. Print and
save period matrix (F). Code the data for S, EXPT, treatment ID.
Calculate number of changes in period that take the direction of the
control condition. Save the matrix in form suitable for spss.

Property of Cynthia Grover, Memorial University of Newfoundland */

#define      LINT_ARGS
#include     <stdio.h>
#include     <stdlib.h>
#include     <string.h>
#include     <malloc.h>
#include     <math.h>

#define sqr(a)             (a * a)
#define max(a,b)  (((a)  > (b)) ? (a) : (b))
#define min(a,b)  (((a)  < (b)) ? (a) : (b))
#define abs(a)             (((a)  < 0) ? -(a) : (a))

/* general-purpose return codes */
#define             SUCCESS        0
#define             FAILURE        (-1)
#define             YES            0
#define             NO             (-1)
#define         LESS_THAN        <
#define         MORE_THAN         >
#define         EQ           ==
#define         ROW          30
#define         COLS         15
#define             VARS                13
#define             MS             30   /* ms per point */
#define             FVARS          18
```

```
int FROM;
int POINTS;
int PU, TFACTOR1;
int STBG, BGP;
int A[80];
int F[ROW][VARS];
int XM[ROW][FVARS];        /* allows for internal id codes */
int RUNS = 0;
int K = 0; /* current row of F matrix */
int W = 0; /* flags Wilcoxon test */
int ANTI = 0;
char STR_ARRAY[ROW][COLS];
char FILENAME[COLS];
/* ---------- Keyboard BUFFER flush --------- */
void kb_flush ()
{
      while ( (char) bdos (0x0B, 0, 0) ) getch ();
}
/* ------ write filename list to register ------ */
save_S()
{
      FILE * unit;
      int result, j;
      char c, regfile[15];

    printf("Save LISTFILE  ___.1 \n");
    kb_flush();
      gets(regfile);
      result = access(regfile,0);
      if (result!= FAILURE) {
            printf("File already exists.\n");
            printf("Use the filename anyway ? \n");
            c = getch();
            if (c!= 'y' && c!= 'Y') return (FAILURE);
      }
      if ((unit = fopen(regfile, "wb"))==NULL) {
```

```
            printf("Can't open the file.\n");
            return (FAILURE);
        }

        else {
          fwrite((char far *)STR_ARRAY, sizeof(char),
                    (ROW*15), unit);
            fclose(unit);
            return(SUCCESS);
        }
}
/* ---- write XM matrix to external file ------ */
save_data()
{
        FILE * unit;
        int result, j;
        char c, outfile[15];

      printf("Save XM file ( __.xm) \n");
      kb_flush();
        gets(outfile);
        result = access(outfile,0);
        if (result!= FAILURE) {
            printf("File already exists.\n");
            printf("Use the filename anyway ? \n");
            c = getch();
            if (c! = 'y' && c!= 'Y') return (FAILURE);
        }
        if ((unit = fopen(outfile, "wb"))= =NULL) {
            printf("Can't open the file.\n");
            return (FAILURE);
        }

        else {
/* fwrite((char far *) &FVARS, sizeof(int), 1, unit);*/
          fwrite((char far *)XM, sizeof(int), (ROW * FVARS),
```

```
                    unit);
            fclose(unit);
            return(SUCCESS);
        }
}
/* ----- read_XM ----------- */
read_XM()
{
int result, j, m;
FILE * unit;
char freqfile[15];

printf ("Read XM file ___.xm\n");
kb_flush();
gets (freqfile);
result = access(freqfile,0);
if (result!= SUCCESS) printf ("File does not exist.\n");

if((unit = fopen(freqfile, "rb"))==NULL) {
        printf("Can't open file. \n");
        return(FAILURE);
        }

/*
result = fread ( (char far *) &FVARS, sizeof(int), 1, unit);
if (result != 1)
        printf ("Error reading number of matrix rows.\n\n");
*/

if (fread((char far *) XM, sizeof(int), (ROW * FVARS), unit)!= 1) {
        if (feof(unit)!= 1) printf("File read. \n");
        }
else {
        printf("Error reading file.\n\n");
        }
fclose(unit);
```

```
for (m = 0; m < 7; m++) {
      for (j = 0; j < VARS; j++) {
            F[m][j] = XM[m][j];
            }
      }
}

/* -----read_F ---------------- */
read_F()
{
int result;
FILE * unit;
char freqfile[15];

printf ("Read SUMMARY file ___.f\n");
kb_flush();
gets (freqfile);
result = access(freqfile,0);
if (result!= SUCCESS) printf ("File does not exist.\n");

if((unit = fopen(freqfile, "rb"))==NULL) {
      printf("Can't open file. \n");
      return(FAILURE);
      }

result = fread ( (char far *) &K, sizeof(int), 1, unit);
if (result != 1)
      printf ("Error reading number of matrix rows.\n\n");

if (fread((char far *) F, sizeof(int), (ROW * VARS), unit)!= 1)
      {
      if (feof(unit)!= 1) printf("File read. \n");
      }
else {
      printf("Error reading file.\n\n");
      }
```

```
fclose(unit);
}
/* --------read_S -------------- */
read_S()
{
/* reads name of .pk files which contributed to F */

int result, j;
FILE * unit;
char regfile[15];

printf ("Read LABEL file ___.l\n");
gets (regfile);
result = access(regfile,0);
if (result!= SUCCESS) printf ("File does not exist.\n");

if((unit = fopen(regfile, "rb"))==NULL) {
      printf("Can't open file. \n");
      return(FAILURE);
      }

if (fread((char far *) STR_ARRAY, sizeof(char), (ROW *15), unit)!= 1)
      {
      if (feof(unit)!= 1) printf("File read. \n");
      }
else {
      printf("Error reading file.\n\n");
      }
fclose(unit);
for (j = 0; j < K; j++) {
      printf("%2d. %s\n", j, STR_ARRAY[j]);
      }
}
/* --- read .pk file (output of spl) ---------*/
read_peak ()
{
```

```
        int result, j;
        char c;
        FILE * unit;

        printf ("Read PEAKFILE ___.pk \n");
        kb_flush();
        gets (FILENAME);

        result = access(FILENAME,0);
if (result!= SUCCESS) printf ("File does not exist.\n");

        if((unit = fopen(FILENAME, "rb"))==NULL) {
                printf("Can't open file. \n");
                return(FAILURE);
                }
        result = fread ( (char far *) &PU, sizeof(int), 1, unit);
        if (result != 1)
printf ("Error reading Peak Up/Down variable.\n\n");

        result = fread ( (char far *) &TFACTOR1,  sizeof(int),
                1, unit);
        if (result != 1)
                printf ("Error reading TFACTOR1.\n\n");

/* makes more sense to record breathgroup length & start
         than FROM & POINTS, given changes to sol.c 12/89 */

        result = fread ( (char far *) &STBG,  sizeof(int), 1, unit);
        if (result != 1)
                printf ("Error reading Start of Group.\n\n");

        result = fread ( (char far *) &BGP,  sizeof(int), 1, unit);
        if (result != 1)
                printf ("Error reading Group length.\n\n");

    if (fread((char far *) A, sizeof(int), 80, unit)!= 1)
```

```
                {
                if (feof(unit)!= 1) printf("File read. \n");
                }
        else {
                printf("Error reading file.\n\n");
                }
        fclose(unit);
        for (j = 0; j < 80; j++) {
                A[j] = A[j] * MS;
        /* conversion to msec from points */
        }
}
/* -------- lag ------------------ */
lag_speech ()
{
int sum_abs, t, c, j, b, n0, start, ref_sp, refl_sp, final, count, sign;
int L[40];   /* half size of A[] */
float mean_abs, tau, sq_tau, tau_sd, sum_tau;
char ch;

printf ("\n-------- Lag Calculation -----------\n");
if (F[K-1][2] < 2 || F[K-1][5] < 2) {
        printf ("Can't calculate lag for row %2d.\n", K-1);
        return (FAILURE);
        }

/*      printf ("Lag:\nTime of the speech peak relative to ");
printf ("the time\nof the nearest non-speech peak\n");
*/

/* search for start */
start = -1;
for (j = 40; j < 80; j++)
        {
        refl_sp = j;
                /* 1st peak is speech reference peak */
```

```
        for (b = 39; b > -1; b--)
              /* search non-speech peaks */
              {
              if (A[b] > 0 && A[b] <= A[refl_sp])
                    {
                    start = b;/* start non-speech ref peak */
                    b = -1;
                    }
              }
        if (b EQ -2) j = 80;  /* non-speech start found */
        }
        if (start != -1)
        {     /* final non-speech reference peak */
              for (b = 0; b < 40; b++)
                    {
                    if (A[b] >= A[refl_sp] && A[b] > A[start])
                          {
                          final = b;
                          b = 41;
                          goto phase;
                          }
                    }
        }
        if (b != 41)
              {
              printf ("Too few data for calculation\n");
              return (FAILURE);
        }

phase:
        count = 1;
        if (A[final] - A[start] EQ 0)
              {
              printf ("division by zero on first cycle\n");
              return (FAILURE);
        }
```

```
    else
        {
        tau = (float) A[refl_sp] - A[start];
        sum_tau = tau / (float) (A[final] - A[start]);
    }
    if ((float)A[refl_sp]- A[start] > (float)(A[final]- A[start])/ 2.0)
        {
        tau = (float) A[refl_sp] - A[final];
        sum_tau = tau / (float)(A[final] - A[start]);
    }
    L[0] = (int)((tau/(float)(A[final] - A[start])) * 100.0);

/* matrix of lag values*/
    sign = 0;
    /* allows unbiased calculations about antiphase
by avoiding zero crosses (enlarges SD) */

    if (ANTI EQ 1 && tau < 0) sign = -1;
    if (ANTI EQ 1 && tau >= 0) sign = 1;
    sq_tau = sqr(tau/(float) (A[final] - A[start]));
    printf ("Cycles used: A[start] = A[%2d]", start);
    t = 1;                          /* matrix index */
    ref_sp = refl_sp;
    for (c = ref_sp + 1; c < 80; c++)
        {
        do
            {
            if (A[c] > 0)
                {
                ref_sp = c; /* speech ref peak */
                j = 80;
            }
            else c++;
        } while (j < 80 && c < 80);

        if (c < 80)
```

```
            {
            for (b = 39; b > -1; b--)
                {
                if (A[b] > 0 && A[b] <= A[ref_sp])
                    {
                    start = b;
                    b = -1;
                }
            }
            if (b EQ -2)
                {
                for (j = 0; j <40; j++)
                    {
        if (A[j] >= A[ref_sp] && A[j] > A[start])
                        {
                        final = j;
                        j = 41;
                    }
                }
            }
            if (j EQ 42)
            {
              if (A[final] > A[start])
                {
/*    if ((float)A[ref_sp]- A[start] > (float)(A[final]- A[start])/ 2.0) */

if ((ANTI EQ 0 && (float)A[ref_sp]-A[start] > (float) (A[final]-
A[start])/ 2.0)|| sign EQ -1)
                    {
                    tau = (float)(A[ref_sp] -A[final])/
                    (float)(A[final] - A[start]);
                    if (tau > 0)
                        {
                    L[t] = (int) ((tau * 100.0) + 0.5);
                    }
                    else {
```

```
                                        L[t] = (int) ((tau * 100.0) - 0.5);
                                        }
                                        t++;
                                        printf (" A[%2d]", start);
                                if (t EQ 8 || t EQ 16) printf ("\n");
                                        sum_tau = tau + sum_tau;
                                        sq_tau = sqr(tau) + sq_tau;
                                }
/*                              else */
                                else if ((ANTI EQ 0 && (float)A[ref_sp]-
A[start] <=(float)(A[final]- A[start])/ 2.0) || sign EQ 1)
                                        {
                                        tau = (float)(A[ref_sp] -A[start!)
                                        /(float)(A[final] - A[start]);
                                        if (tau > 0)
                                               {
                                        L[t] = (int) ((tau * 100.0) + 0.5);
                                        }
                                        else {
                                        L[t] = (int) ((tau * 100.0) - 0.5);
                                        }
                                        t++;
 /* n of values already stored. storage starts at index 0 */
                                if (t EQ 8 || t EQ 16) printf ("\n");
                                        printf (" A[%2d]", start);
                                        sum_tau = tau + sum_tau;
                                        sq_tau = sqr(tau) + sq_tau;
                                        }
                                }
                        }
                }
        }
        for (j = t; j < 40; j++)
                { /* zero remainder of L[]*/
                L[j] = 0;
        }
```

```
        sum_abs = 0;
        for (j = 0; j < t; j++) {
              sum_abs = abs(L[j]) + sum_abs;
        }
        mean_abs = (float) (sum_abs) / (float) (t);

/*      count = ref_sp - ref1_sp;
        tau_sd = sqrt ((sq_tau - (sqr(sum_tau)/ (float)(count))) /
(float)(count - 1));
        tau = sum_tau * 100.0 / (float) count; */

        tau_sd = 100.0 * sqrt ((sq_tau - (sqr(sum_tau)/ (float)(t))) /
(float)(t - 1));  /* n - 1 SD */
        tau = sum_tau * 100.0 / (float) (t);
/*      printf ("tau: %6.2f  sum_tau: %6.2f  tau_sd: %9.4f t: %3d \n",
tau, sum_tau, tau_sd, t); */

        if (tau > 0 ) F[K-1][6] = (int) (tau + 0.5);
        else F[K-1][6] = (int) (tau - 0.5);
        F[K-1][7] = (int) (tau_sd + 0.5);
        F[K-1][8] = t;
        printf ("Lag Matrix\n\n");
        printf ("Peak  Lag   Peak  Lag   Peak  Lag");
        printf ("   Peak  Lag\n");
        for (j = 0; j < 10; j++) {
printf ("%4d  %4d   %4d  %4d   %4d  %4d   %4d  %4d\n",
        j, L[j], j+10, L[j+10], j+20, L[j+20], j+30, L[j+30]);
              }
        printf ("\nMean Lag  SD   N   Mean Abs Lag\n");
        printf ("%5d  %5d  %3d       %5.1lf\n", F[K-1][6],
              F[K-1][7], F[K-1][8], mean_abs);
        ANTI = 0;
}
/*--------- calculate and sort proportions ----*/
prop()
{
```

```
int c;
double prop, syn;

for (c = 0; c < K; c++) {
        if (F[c][3] > 0 && F[c][0] > 0) {  /* non-zero means */
                if (F[c][0] > F[c][3]) {
                        F[c][10] = 0;
        /* 0 -> forc longer period (lower F) than sp*/
                        F[c][9] = (int)((100 * (double) F[c][0]/
                                (double) (F[c][3])) + 0.5);
        /* proportion as percent to keep in integer form */
                        }
                else {
                        F[c][10] = 1;
        /* 1 for forc shorter period (higher freq) than sp */
                        F[c][9] = (int)((100 * (double) F[c][3]/
                                (double) (F[c][0])) + 0.5);
                }
                prop = (double) F[c][9] / 100.00;
                syn = (prop - ((int) prop)) * 100.00;
                F[c][12] = (int) syn;
/* measure of entrainment. values 0 = synchronous; 50 = asynchronous
*/
        }
        else {
                F[c][9] = 0;
                F[c][10] = 0;
/*              F[c][11] = 0;      */
                }
        }
}
/*------- Mean Period, stdev calcs ----------- */
freq ()
{
int c, j, n0, n1, speech;
double  sum, sum0, sum1, mean0, mean1, dev, dev0, dev1, stddev0,
```

```
stddev1;

printf ("Filing summary statistics in matrix\n");

    /* find n per channel in A matrix */
for (c = 39; c > -1; c--) {
    if (A[c] > 0) {
        n0 = c + 1;        /* storage starts at index 0 */
        break;
        }
    if (c EQ 0) {
        printf ("File contains only speech data\n");
        n0 = 0;
        speech = 1;
        F[K][11] = 1;
        }
    }

for (c = 79; c > 39; c--) {
    if (A[c] > 0) {
        n1 = (c - 40) + 1;
        break;
        }
    if (c EQ 40) {
        printf ("File contains only non-speech data\n");
        speech = 0;
        n1 = 0;
        F[K][11] = 0;
        }
    }

if (speech != 0 && speech != 1) speech = 2;

/* F matrix: 1 row per pk file.  Each row contains:
F[K][0]: mean non-speech inter-peak period
F[K][1]: standard deviation non-speech inter-peak period
```

```
F[K][2]: number of non-speech subtractions (n)
F[K][3]: mean speech inter-peak period
F[K][4]: standard deviation speech inter-peak period
F[K][5]: number of speech subtractions (n)
F[K][6]; mean lag
F[K][7]; standard deviation of lag
F[K][8]; number of lag subtractions
F[K][9]: proportion of speech to non-speech period
F[K][10]: speech/non-speech =1; non-speech/speech = 0
F[K][11]: speech only = 1; non-speech only = 0; both = 2
F[K][12]; measure of entrainment between speech and forcer
      * extensions with XM*
F[K][13]: Subject Number
F[K][14]: Experiment Number
F[K][15]: Session Number
F[K][16]: junk = 0; or Wilcoxon score
F[K][17]: junk = 0; or direction of trend for Wilcoxon
*/
      /* calculate means and stdevs. */
sum = 0.00;  sum1 = 0.00;  sum0 = 0.00;
dev0 = 0.00;      dev1 = 0.00;

/* divisions by 30 to keep integers less than 32678 */

if (speech != 1) {
      for (c = 0; c < n0 - 1; c++) {
      sum = ((float)A[c+1]/30.00) - ((float)A[c]/30.00);
      sum0 = sum + sum0;
      }
mean0 = (sum0 / ((double) n0 - 1.0)) * 30.00;
        /* sb = A[n0-1]/n0-1  */
F[K][0] = (int) (mean0 + 0.5);
 /*(int) truncates. +.5 rounds */
/*    printf("mean NON-speech: %6.2lf\n", mean0);  */
/* There is one subtraction fewer than there are peaks: thus n - 1 */
```

```
for (c = 0; c < n0 - 1; c++) {
      dev = ((double)(A[c+1]/30.00) - (double)(A[c]/30.00))
                           - (mean0/30.00);
      dev = sqr (dev);
      dev0 = dev + dev0;
      }
stddev0 = (sqrt (dev0 / (n0 - 1))) * 30.00;
F[K][1] = (int) (stddev0 + 0.5);
            /* This is stdev based on n, NOT n - 1 */
/* printf("F[K][1] %5d\n\n", F[K][1]);  */
}

if (speech != 0) {
      for (c = 40; c < n1 + 39; c++) {
            sum = (double)(A[c+1]/30.00) -
                  (double)(A[c]/30.00);
            sum1 = sum + sum1;
            }
      mean1 = ((double) sum1 / (n1 - 1)) * 30.00;
      F[K][3] = (int) (mean1 + 0.5);
     /* number of subtractions */
/* printf("mean speech: %6.2lf\n", mean1);      */
      for (c = 40; c < n1 + 39; c++) {
            dev = ((double)(A[c+1]/30.00) -
            (double)(A[c]/30.00))- (mean1/30.00);
            dev = sqr (dev);
            dev1 = dev + dev1;
            }
      stddev1 = (sqrt (dev1 / (n1 - 1))) * 30.00;
      F[K][4] = (int) (stddev1 + 0.5);
/*    printf("F[K][4] %5d\n", F[K][4]);    */
      }

F[K][11] = speech;
F[K][2] = n0 - 1;  F[K][5] = n1 - 1;
 /* true n: n of subtractions */
```

```
if (speech EQ 1) F[K][2] = 0;
if (speech EQ 0) F[K][5] = 0;
/*    printf ("K: %2d, FROM: %4d, POINTS: %4d \n\n", K, FROM,
POINTS); */
printf ("\nSummary of Row %d %8.15s\n\n", K, STR_ARRAY[K]);
printf ("Mean NON    Sd   N       Mean SP     Sd   N\n\n");
printf ("%5d  %7d  %2d       %5d  %7d  %2d\n",F[K][0], F[K][1],
F[K][2], F[K][3], F[K][4], F[K][5]);
K++;              /* increment for next F row */
if (speech EQ 2) {
      lag_speech();
      prop();
      }
}
/* ---------- print peakfile contents ----------------- */
show_data ()
{
int j;
char c;

printf ("Press ENTER to print contents of %s\n", FILENAME);
kb_flush();
do { } while (getch() != '\r');
printf("\n                %s\n", FILENAME);
/*    if (P0 EQ 32) prop0 = 0.33;
      else prop0 = (float) (P0) / 10.0;
      if (P1 EQ 32) prop1 = 0.33;
      else prop1 = (float) (P1) / 10.0;
printf("Prop. MAXPK0: %6.2f, Prop. MAXPK1: %6.2f, FROM %d,
POINTS %d\n", prop0, prop1, FROM, POINTS);    */

printf ("TFACTOR1: %3d      STBG: %5d (ms)          ");
printf (" BGP: %5d (ms)\n\n", TFACTOR1, STBG*30, BGP * 30);
if (PU < 1) printf ("Peaks picked in narrow gaps\n\n");
else if (PU < 2) printf ("Peaks picked in wide gaps\n\n");
else printf ("PU irrelevant");
```

```
printf ("Channel 1 (Other)              Channel 2"); printf
("Speech/Finger)\n");
for (j = 0; j < 20; j++) {
      printf("A[%2d]: %5d  A[%2d]: %5d", j, A[j], j+20,
            A[j+20]);
      printf("     A[%2d]: %5d  A[%2d]: %5d\n", j+40,
            A[j+40], j+60, A[j+60]);
      if (j EQ 4 || j EQ 9 || j EQ 14) printf ("\n");
      if (j EQ 9) {
            printf ("Press ENTER for rest of display\n");
            kb_flush();
            do { } while (getch() != '\r');
            }
      }
}
/*------------ Zero calibration data ------------ */
zero_right()
{
int j;
char ch, c, x[2];

printf ("Zero calibration data (non-finger) ? (y/n) \n");
kb_flush();
c = getch();
if (c EQ 'y' || c EQ 'Y') {
      for (j = 0; j < 40; j++) {
            A[j] = 0;
            }
      }
else {
      printf ("Zero peak A[x]. Type x.\n x:");
      kb_flush();
      gets(x);     j = atoi(x);
      printf ("Zero A[%2d]: %5d (y/n) ?\n", j, A[j]);
      kb_flush();
      ch = getch();
```

```
        if (ch EQ 'y' || ch EQ 'Y') A[j] = 0;
        }
}
/* ----------- kill current matrix ---------------- */
kill_matrix()
{
        int j, a;
        char c;

printf ("\nDo you want to zero the F");
printf (" matrix (y/n) ?\n");
kb_flush();
c = getch();
if (c EQ 'y' || c EQ 'Y') {
        for (j = 0; j < ROW; j++) {
                strcpy(STR_ARRAY[j], "0");
                for (a = 0; a < VARS; a++) {
                        F[j][a] = 0;
                        }
                }
        }
        K = 0;
}
/*  ------ print summary table ---------------- */
print_table()
{
int j, b, sou, dest, temp;
char c, ch, str[5];

printf("Summary table\n\n");
printf("\nPr (Proportion): Mean Period Non-Speech : Mean Period
Speech\n");
printf("Dir (Direction of Proportion): ");
printf("0: speech faster, forcer slower\n");
printf("                              ");
printf("1: speech slower, forcer faster\n");
```

```
printf("Origin: 0: forcer real, speech random\n");
printf("        1: speech real, forcer random\n");
printf("        2: speech real, forcer real\n\n");
printf("Row M Non  Sd  N    M Sp  Sd  N    M Ph  Sd  N");
printf ("  Pr Dir Or Sync  File.pk\n\n");
for (j = 0; j < K; j++) {
      printf("%2d  %4d %3d %3d   %4d", j, F[j][0],
            F[j][1], F[j][2], F[j][3]);
printf(" %4d %3d   %4d  %4d %2d %3d  %d  %d  %2d %8.15s\n",
            F[j][4], F[j][5], F[j][6], F[j][7], F[j][8], F[j][9], F[j][10],
F[j][11], F[j][12],                STR_ARRAY[j]);
      }
      printf ("\nExit:x  Choose Row:c  Delete Row:d \n");
      kb_flush();
      switch(getch()) {
            case 'x':
            case 'X':
                  return (SUCCESS);
                  break;
            case 'C':
            case 'c':
printf ("Reorder Rows. Enter number of row to move.\n");
                  kb_flush();
                  gets(str);
                  sou = atoi(str);
                  printf ("Move row %2d\n", sou);
                  printf ("Insert in front of which row ?\n");
                  kb_flush();
                  gets(str);
                  dest = atoi(str);
printf ("Row %2d goes to row %2d\n", sou, dest);
                  temp = K+1;
                  for (j = temp; j > dest - 1; j--) {
                        for (b = 0; b < VARS; b++) {
                              F[j+1][b] = F[j][b];
                        }
```

```
                        strcpy(STR_ARRAY[j+1], STR_ARRAY[j]);
                  }
                  if (dest < sou) sou = sou + 1;
                  for (b = 0; b < VARS; b++) {
                        F[dest][b] = F[sou][b];
                  }
                  strcpy(STR_ARRAY[dest], STR_ARRAY[sou]);
                  for (j = sou; j < temp; j++) {
                        for (b = 0; b < VARS; b++) {
                              F[j][b] = F[j+1][b];
                        }
                  }
                  break;
            case 'd':
            case 'D':
                  printf ("Delete which Row ?\n");
                  kb_flush();
                  gets(str);
                  dest = atoi(str);
                  printf ("Row %2d\n", dest);
printf("Row M Non  Sd  N    M Sp  Sd  N    M Ph  Sd  N");
printf ("  Pr Dir Or Sync  File.pk\n\n");
printf("%2d  %4d %3d %3d   %4d", j, F[dest][0], F[dest][1],
                  F[dest][2], F[dest][3]);
printf(" %4d %3d   %4d  %4d %2d %3d  %d  %d   %2d %8.15s\n",
F[dest][4], F[dest][5], F[dcst][6], F[dest][7], F[dest][8],
F[dest][9], F[dest][10], F[dest][11], F[dest][12],
                  STR_ARRAY[dest]);
                  printf ("\nHit 'd' to delete this row.");
                  printf ("  Else hit ENTER\n");
                  kb_flush();
                  ch = getch();
                  if (ch EQ 'd' || getch() EQ 'D') {
                        for (j = dest; j < K; j++) {
                              for (b = 0; b < VARS; b++) {
                                    F[j][b] =F[j+1][b];
```

```
                    }
                strcpy(STR_ARRAY[j], STR_ARRAY[j+1]);
                }
                K--;
            }
            break;
    } /* end switch */
}
/* ------------ print XM ------------------------ */
print_XM ()
{
    int j;

printf("Row M Non  Sd  N    M Sp  Sd  N    M Ph  Sd  N");
printf ("  Pr Dir Or Sync NUM EX SES 0 0\n\n");
for (j = 0; j < 7; j++) {
    printf("%2d  %4d %3d %3d   %4d", j, XM[j][0],
    XM[j][1], XM[j][2], XM[j][3]);
printf(" %4d %3d  %4d  %4d %2d %3d  %d  %d  %2d %2d %2d",
    XM[j][4], XM[j][5], XM[j][6], XM[j][7], XM[j][8], XM[j][9],
XM[j][10], XM[j][11], XM[j][12], XM[j][13], XM[j][14]);
printf (" %2d %2d %2d\n", XM[j][15], XM[j][16], XM[j][17]);
    }
}
/* -------code file --------------------------*/
code_file ()
{
    int j, num, ses, exp, m;
    char input[4];
printf ("Add subject, session, experiment ID to file\n");
printf ("Subject Number ? (1-20)\n");
printf ("1 CD  2 PB  3 LR  4 CR  5 MP  6 KK  7 SN");
printf ("  8 MJ \n");
printf ("9 YA  10 HB  11 SB  12 AF  13 SOL 14 BP  15 JT\n");
kb_flush();
gets(input);
```

```
num = atoi(input);
printf ("Experiment type ? (1-8)\n");
printf ("FC: 1  SC: 2  FA: 3  FB: 4  FS: 5  SA: 6  SB: 7");
printf ("  SS: 8\n");
kb_flush();
gets(input);
exp = atoi(input);
printf ("Session Number ? (1-10)\n");
kb_flush();
gets(input);
ses = atoi(input);
for (m = 0; m < 7; m++) {
      for (j = 0; j < VARS; j++) {
            XM[m][j] = F[m][j];
            }
      XM[m][VARS] = num;
      XM[m][VARS+1] = exp;
      XM[m][VARS+2] = ses;
      if (W EQ 0) {
            XM[m][VARS+3] = 0;
            XM[m][VARS+4] = 0;
            }
      }
print_XM ();
}
/* ----------- Wilcoxon tests ---------------- */
wilcoxon ()
{
      int j  pos, dir, neg, num;
      char input[4];

printf ("control condition direction");
printf (" (1 slows/ -1 speeds/ 0) ?\n");
kb_flush();
gets(input);
dir = atoi(input);
```

```
printf ("Period: %5d\n", XM[0][3]);
pos = 0;    neg = 0;    num = 0;
for (j = 0; j < 6; j++) {
      if (((dir EQ 1 || dir EQ 0) && XM[j+1][3] > XM[j][3])     ||
(dir EQ -1 && XM[j+1][3] < XM[j][3]))
            {      /* matches control; default is slowing */
            XM[j][16] = -1;
            printf ("Matches control trend  \n");
            pos++;
            }
      else if (XM[j+1][3] EQ XM[j][3]) {
            XM[j][16] = 0;
            }
      else {
            XM[j][16] = 1;
            neg++;
            }
      printf ("Period: %5d     Direction: %d\n", XM[j+1][3],
                  XM[j][16]);
      }
if (dir EQ 0 && (XM[0][3] - XM[6][3]) > 0)
      {
      XM[6][17] = -1; /* control speeds up */
      }
else XM[6][17] = 1; /* default: control slows down */
if (dir EQ 1 || dir EQ -1) XM[6][17] = dir;

/*    if (dir EQ 0 && XM[6][17] EQ -1) num = neg;
      if (dir EQ 0 && XM[6][17] EQ 1) num = pos;
      if (dir != 0 && pos < neg) num = neg;
      else num = pos;
for SS whose overall trend did not show up in
majority of sample intervals    */

if (dir EQ 0) {
      if (pos < neg) num = neg;
```

```
        else num = pos;
        }
else num = pos;

 /* score = # appropriate directional trends */
printf ("Number of slopes in control trend: %d\n", num);

for (j = 0; j < 6; j++) XM[j][17] = 0; /* zeros matrix */
XM[6][16] = num;       /* score for Wilcoxon test */
W = 1;
}
/* ----------- main --------------------------*/
main ()
{
char c;
int j;
        /* --------------MENU------------*/

for (;;) {             /* forever */
        printf ("\n------------\n\n                MENU\n\n");
        kb_flush();
        printf ("W R S J B G Z K C F A T L X P Q;");
        printf (" H (Help)\n\n");
        printf ("Press one of the above keys\n");
        printf ("------------------------------\n");
        switch (getch()) {
                case 'h':
                case 'H':
                        printf ("    Help\n\n");
printf ("R Read a summary table of peakfiles\n");
                        printf ("W Write the XM table of data\n");
                        printf ("G Get a peakfile\n");
printf ("Z Zero calibration data (right channel)\n");
printf ("C Calculate the summary table values\n");
printf ("F File Period, Lag, Entrain Index \n ");
printf ("L Calculate speech-stimulus lag\n");
```

```
printf ("S Show the current peakfile data\n");
printf ("T Type the summary table to screen\n");
printf ("K Kill the F matrix\n");
printf ("X Expand matrix with coding \n");
printf ("B Read an XM table file\n");
printf ("J Calculations for Wilcoxon test\n");
printf ("P Print XM table\n");
printf ("A Calculate lag for antiphase files\n");
                printf ("Q Quit\n");
                break;
        case 'r':
        case 'R':
                read_F();
                read_S();
                break;
        case 'W':
        case 'w':
                 save_data();
                 break;
        case 'b':
        case 'B':
                read_XM ();
                break;
        case 'j':
        case 'J':
                wilcoxon ();
                break;
        case 'p':
        case 'P':
                print_XM ();
                break;
        case 'g':
        case 'G':
                printf ("Get a peakfile.\n\n");
                printf("Files in the F matrix so far:\n");
                for (j = 0; j < K; j++) {
```

```
                printf("%8.15s\n", STR_ARRAY[j]);
                }
            read_peak();
            break;
        case 'Z':
        case 'z':
            zero_right();
            break;
        case 'A':
        case 'a':
            ANTI = 1;
printf ("Press L or F for antiphase calculation\n");
            break;
        case 'S':
        case 's':
            show_data();
            break;
        case 'F':
        case 'f':
            memcpy(STR_ARRAY[K],FILENAME,COLS);
            freq();
            break;
        case 'l':
        case 'L':
            printf ("Calculate lag\n");
            lag_speech();
            break;
        case 'k':
        case 'K':
            printf ("Kill the current F matrix");
            kill_matrix();
            break;
        case 'c':
        case 'C':
            printf ("Calculate summary table\n");
            prop();
```

```
                        break;
                case 'x':
                case 'X':
                        printf ("Introduce codes for statistics \n");
                        code_file();
                        break;
                case 't':
                case 'T':
                        print_table();
                        break;
                case 'q':
                case 'Q':
                        printf ("Quit\n");
                        goto bottom;
                }       /* end switch */
        }       /* end for loop */
        bottom:
                printf ("Bye\n");
                exit (0);
}
```

SMALL.C

```
/* Program which records about 2 sec of sound on 2 channels, displays
oscilloscope style graphs of amplitude vs time for the raw sound and of
power vs time for the smoothed POWer contour. Plotter displays and
playback via DACs, write to disk functions too. Raw: 16384 pts * 2
channels; sampled at 100 Khz (50 Khz each) divided by TDIV, usually 7
: sampling rate = 7143 Hz per channel (approx). One point of data
represents 0.14 ms. SCANS and TDIV in file header. For the POWer
data: 128 points (16384/LENV (usually 128)) total for the total time of
2.3 secs. 18 ms per point of POWer data. Header contains LENV and
TDIV. Program assumes graph on screen of POWer data before plot on
plotter, and that speech is recorded on channel 1, other on channel 0.

Property of C. Grover, Memorial University of Newfoundland, 1991 */

#define         LINT_ARGS

#include    <stdio.h>
#include    <stdlib.h>
#include    <string.h>
#include    <malloc.h>

#include    <math.h>
#define max(a,b)  (((a) > (b)) ? (a) : (b))
#define min(a,b)  (((a) < (b)) ? (a) : (b))
#define abs(a)          (((a) < 0) ? -(a) : (a))

#include    <herc.h>
#include     "tek.h"

      /* general-purpose return codes */
#define         SUCCESS      0
#define         FAILURE      (-1)
#define         YES          0
#define         NO           (-1)
```

```
#define      LESS_THAN      <
#define      MORE_THAN       >
#define      EQ             ==
#define          MASTER
#include    <labhead.h>
extern int labpac(int,...);

/* ---------- globals ---------- */
int huge * BUFFER;
int AMPL[1024][2];
int POW[1024][2];
int A[10][3];
/* int THRESH, THR1;        */
int FROM;
int POINTS;
int TDIV = 7;
int SCANS = 16384;
int ADIV = 4;
int W  = 5, WLIST[6] = {1, 2, 5, 10, 20, 40};
/* first element in this series would have index 0.   40 = usual value */
double XSCALE;
char FILENAME[15];
char DATE[11];
char GRID[32768];
#define LENV     (128)
#define SCANS    (16384)

/* char GRID[32768]; */
#define GRID ( (char far *) 0xb8000000)

/* ---------- Keyboard buffer flush ---------- */
void kb_flush ()
{
     while ( (char) bdos (0x0B, 0, 0) ) getch ();
}
```

```
/* ---------- check for a loaded vector ---------- */
/* Is LabPac there? If so, there should be a vector for INT 0x66. */

/* ------------------------- */
void check_vector(v)
      int v;
{
      unsigned long far * zero = 0x00000000;

      if (v  < 0 | | v > 255) {
            printf ("No such interupt.\n");
            exit(FAILURE);
      }

      if ( *(zero + v) = = 0L) {
printf ("ERROR: Vector %xH isn't loaded.%c\n", v, 7);
            exit(FAILURE);
      }
}

/* ---------- long-to-pointer conversions ---------- */

union HUGE_PTR {
      int huge * ptr;
      unsigned int i[2];
};

int huge * ltop (a)
      unsigned long a;
{
      union HUGE_PTR p;
      p.i[0] = a % 16;
      p.i[1] = a / 16;
      return (p.ptr);
}
```

```
unsigned long ptol (p)
      union HUGE_PTR p;
{
      unsigned long a;
      a   = p.i[1];
      a <<= 4;
      a  += p.i[0];
      return (a);
}

/* ---------- record sound sample ---------- */
int record ( p)
      int huge *p;
{
      int oldintr, result, j;

      if (TDIV < 3) {
            TDIV = 3;
            printf ("<TDIV> increased to 3.\n");
      }

      /*----- SCANS = 16384 * 2 channels -------*/
      oldintr = labpac (INTCLR, 255);    /* turn off all interrupts */
      labpac (TIST, 5, 12, TDIV);         /* 12 == 100 kHz */
      labpac (TIST, 4,  3,   0);      /* count conversions */

      printf ("\n\nR E C O R D I N G . . .\n\n");
      result = labpac (AIDMA, 0, SCANS, 2, p);
      if (result) {
            printf ("AIDMA error = %xH.\n", result);
            labpac (INTSET, oldintr);
            labpac (RESET);
            return (FAILURE);
      }

      labpac (TISTAT, 4, SCANS * 2);
```

```
        labpac (TIAB, 4);
        labpac (TIAB, 5);
        labpac (INTSET, oldintr);       /* restore interrupts */
        printf ("Recording done.\n");
        return (SUCCESS);
}

/* -----------write raw data to external file --------- */
save_raw()

{
        FILE * unit;
        int result, blank;
        char c, rawfile[15];

        kb_flush();
        text_mode();
        printf("Datafile ?\n");
        gets(rawfile);

        blank = SCANS;

        result = access(rawfile,0);
        if (result!= FAILURE) {
                printf ("File already exists.\n");
                printf ("Use the filename anyway ? \n");
                c = getch();
                if (c!= 'y' && c!= 'Y') return (FAILURE);
        }

        if ((unit = fopen(rawfile, "wb"))==NULL) {
                printf ("Can't open the file.\n");
                return (FAILURE);
        }
        else {
                fwrite( (char far *) &blank, 2, 1, unit);
```

```
            fwrite( (char far *) &TDIV, 2, 1, unit);
        fwrite( (char far *) BUFFER, sizeof(int), (SCANS * 2), unit);
            fclose(unit);
            return(SUCCESS);
      }
}

/* -----------write POWer data to external file --------- */
save_POW()

{
      FILE * unit;
      int result, blank;
      char c, intfile[15];

    kb_flush();
    text_mode();
    printf("Filename ?\n");
      gets(intfile);
    blank = LENV;
      result = access(intfile,0);
      if (result!= FAILURE) {
            printf("File already exists.\n");
            printf("Use the filename anyway ? \n");
            c = getch();
            if (c!= 'y' && c!= 'Y') return (FAILURE);
      }

      if ((unit = fopen(intfile, "wb"))==NULL) {
            printf("Can't open the file.\n");
            return (FAILURE);
      }
      else {
            fwrite( (char far *) &blank, 2, 1, unit);
            fwrite( (char far *) &TDIV, 2, 1, unit);
            fwrite( (char far *) POW, sizeof(int), (SCANS/LENV) * 2,
```

```
unit);
            fclose(unit);
            return(SUCCESS);
      }
}

/* ---------- load data from file ---------- */
read_data()
{
      int result, blank;
      FILE * unit;

      if ((unit = fopen (FILENAME, "rb") )==NULL) {
            printf ("Can't open file. \n");
            return (FAILURE);
      }

      printf("File open. \nReading..\n");
      result = fread ( (char far *) &blank, sizeof(int), 1, unit);
      if (result != 1)
            printf ("Error reading SCANS.\n\n");

      result = fread ( (char far *) &TDIV,  sizeof(int), 1, unit);
      if (result != 1)
            printf ("Error reading TDIV.\n\n");

      result = fread ( (char far *) BUFFER, sizeof(int), (SCANS * 2),
unit);
      if (result != (SCANS * 2))
      printf ("Error reading data-- file seems short.\n\n");
      fclose(unit);
      printf("SCANS %d, TDIV %d \n\n", blank, TDIV);
}

/* -- two scope-like grids, 4 div high * 10 div wide - */
void make_grid()
```

```
{
      int j;

for (j =  10; j < 171; j += 40) hor_line (0, j, 500, j, 1);
for (j = 180; j < 341; j += 40) hor_line (0, j, 500, j, 1);
      for (j =   0; j < 501; j += 50) {
            line ( j,  10, j, 170, 1);
            line ( j, 180, j, 340, 1);
      }

    Ggoto_xy (1, 65);
      gtext ("Raw data");

      Ggoto_xy (3, 65);
    gtext ("Page ___ of ___");

      Ggoto_xy (5, 65);
      gtext ("CV/div ______");

    Ggoto_xy (7, 65);
    gtext ("MS/div ______");

    Ggoto_xy (9, 65);
    gtext ("FROM _______");

    Ggoto_xy (11, 65);
    gtext ("POINTS ______");

    Ggoto_xy (15, 65);
      gtext ("POWER data");

      Ggoto_xy (17, 65);
      gtext ("Page ___ of ___");

    Ggoto_xy (19, 65);
    gtext ("CV2/div ______");
```

```
    Ggoto_xy (21, 65);
    gtext ("MS/div ______");

    Ggoto_xy (23, 65);
    gtext ("INT pts/div ______");

}

/* --- plot the raw data; second-level function - */
void plot_raw (page, AD_pt)
      int page, AD_pt;
{
      int pages, pix_div, width, j, y, lastv;
      int huge *p;
      float ms_div, cv_div;
      char string[40];

      width = WLIST[W] * 512;
      pages = (long) (16384L + width - 1L) / width;
      page = min (page, pages-1);
      p = BUFFER + page * width * 2;
      POINTS = min (16384 - page * width, width);

    pix_div = 2000/pages;        /* total = 20000 pts/10 div/pages */
    ms_div = (float) pix_div * (float) TDIV/50.00;
 /*-- convert to ms per div = ms/pt * (pts/div)/pages. TDIV = 7;
sampling rate sb 7143 Hz; actually about 7250 Hz.  /1000 cycles/MSEC
(in msec, not sec)   */

      cv_div = AD_pt * 40 / 8;
/* convert to APPROXIMATE cv/div = A-D units/per screen pt    * 40
screen pt/div * 100 cv/800 A-D units. The data come off the A to D
board in no particular units (volts of some sort). AD_pt converts these
data to points out of 160 to plot on screen. 1/8 converts these data to cv.
40 converts the labels for the screen plot divisions. other j = 0, p at 000;
```

```
speech 002 ; other plots in lower screen. speech plots in upper half */

        memcpy (PAGE0, GRID, 32768);
        for (j = 0; j<POINTS; j++) {
              y = *p++ / AD_pt;
              set_pix (j/WLIST[W], 260 - y, 1);
              y = *p++ / AD_pt;
              set_pix (j/WLIST[W], 90 - y, 1);
        }

        Ggoto_xy (3, 70);
        sprintf (string, "%3d", page + 1);
        gtext (string);

        Ggoto_xy (3, 77);
        sprintf (string, "%3d", pages);
        gtext (string);

        Ggoto_xy (5, 72);
          sprintf (string, "%6.2f", cv_div);
          gtext (string);

        Ggoto_xy (7, 72);
        sprintf (string, "%7.2f", ms_div);
        gtext (string);

        Ggoto_xy (9, 72);
        sprintf (string, "%4d", FROM);
        gtext (string);

        Ggoto_xy (11, 72);
        sprintf (string, "%4d", POINTS);
        gtext (string);

}
```

```
/* ---------- play the raw data out the DACs --------- */
void playback (page)
        int page;
{
        static int channels[2] = {0, 1};
        int pages, result, width, j, y;
        int huge *p;

        width = WLIST[W] * 512;
        pages = (long) (16384L + width - 1L) / width;
        page = min (page, pages-1);
        p = BUFFER + page * width * 2;

        Ggoto_xy (12, 65);
        gtext ("Audio.");
        labpac (TIST, 1, 12, TDIV);
        result = labpac (AOMAX, 1, POINTS, 2, channels, p);
        Ggoto_xy (12, 65);
        if (result) gtext ("-FAILURE-");
        else gtext ("          ");
}

/* ---------- send data to plotter ---------------- */
void send_data (page, chn)
        int page, chn;
{
        int pages, amp, width, j, k, temp, cv;
        double hix, hiy, lox, loy;
        float ms_pt, msec;
        int huge *p;
        char string[60], xlabel[10], ylabel[10];

        FILE * unit;
        unit = fopen ("COM2", "wb");
        TekInit (unit, 'D'):
        TekCharSize (0.18, 0.30);
```

```
        TekFxd (0, 0);

        if (chn EQ 1) k = 0;
        else k = 1; /* chnnl 1 other k =0; chnnl 2 speech k =1 */
      if (k == 0) TekWindow (0.50, 6.50, 0.40, 4.40);
        if (k == 1) TekWindow (0.50, 6.50, 5.60, 9.60);
/* Speech at top of paper.  Move paper 0.5" to right of graph tablet.
(Labels don't print if 0.00, 6.00 specified). Leaves 0.5 margin */

        width = WLIST[W] * 512;

/* ADIV = set {1,2,4,8,16,32} decreases range plotted */

        if (ADIV == 6) amp = 5120;
        if (ADIV == 5) amp = 2560;
        if (ADIV == 4) amp = 1280;
        if (ADIV == 3) amp = 640;
        if (ADIV == 2) amp = 320;
        if (ADIV == 1) amp = 160;

     (int) cv = amp * 0.125;
/* total cv = 40 screen pts/div * A-D units/pt * 1 cv/   */
/* 8 A-D units * 4 divisions. real range = + to - cv   */

        pages = (long) (16384L + width - 1L) / width;
        page = min (page, pages-1);
        p = BUFFER + page * width * 2;

        ms_pt = (float) TDIV / 50.00;
 /*50000 hz/1000 ms/sec=cycles/msec */
        msec = ms_pt * POINTS;
/*      fprintf (stdprn, "msec = %10.2f\n", msec);
        fprintf (stdprn, "ms_pt = %10.2f\n", ms_pt);   */
/* real time msec per pt: div. sampling freq by 50 Hz * total points =
total msec in sample */
        TekScale (0.00, (double)msec, -(double)cv,      (double)cv);
```

```
      TekGrid ((double)msec/4.00, (double)cv/2.00, 0.00,
          -(double)cv, 4, 4);
      for (j = -cv/2; j < cv; j += cv/2) {
      TekMove (0.00, (double)j);
      TekDraw ((double)msec, (double)j);
    }
    for (j = (int)msec/4; j < (int)msec; j += (int)msec/4) {
         TekMove ((double)j, (double)(-cv));
         TekDraw ((double)j,  (double)cv);
    }

    TekCharSize (0.18, 0.30);
    TekLAxes (-(double)msec/4.00, -(cv/2.00), 0.00,
         -(double)cv);
    TekMove (0.00, 0.00);
    TekCharSize (0.18, 0.30);

/* -- j=50 yields about 72 zero crossings per inch -- */

    if (k EQ 1) p++;
/* speech. this agrees with plot_raw, and print_: 000 OTHER value */

    for (j = 0; j<POINTS; j+=64) {
         hiy = *p++;
         loy = hiy;
         hix = j * ms_pt;
         lox = j * ms_pt;
         p++;

         for (k=0; k<63; k++) {
              temp = *p++;
              if (temp > hiy) {
                   hiy = temp;
                   hix = (j + k) * ms_pt;
                   }
              if (temp < loy) {
```

```
                        loy = temp;
                        lox = (j + k) * ms_pt;
                        }
                  p++;
                  } /* end for k */

      /* A-D units * 1 cv/8 A-D units     */

            if (hix > lox) {
                  TekDraw ((double)lox, (double)loy * 0.125);
                  TekDraw ((double)hix, (double)hiy * 0.125);
                  }
            else {
                  TekDraw ((double)hix, (double)hiy * 0.125);
                  TekDraw ((double)lox, (double)loy * 0.125);
                  }
            }

sprintf (string, "Ch %d Raw %s file %s  page %2d of %2d",
                 chn, DATE, FILENAME, page + 1, pages);
/* \x0b moves the label plot up twice the char height */
      TekMove (5.00, (double)cv);
      TekLbOrg (1);
      TekLabel (string);
      sprintf (xlabel, "\x0a\x0a msec");   /* \x0a = move plot down */
    TekMove ((double)msec/8.00, (double)-cv);
    TekLbOrg (4);
    TekLabel (xlabel);
      sprintf (ylabel, "cv");  /* \x08 = move plot left */
      TekMove ((double)-msec/8.00, (double) cv/4.00);
    TekLbOrg (5);
    TekLabel (ylabel);
    sprintf (string, "\x07"); /* beep to signal plot end */
    TekLabel (string);
      fflush (unit);
}
```

```
/* - square function used in POWer plot ----- */
sqr (x)
float x;
{
        x = x * x;
        return(x);
}

/* - show the raw data; calls above routine ------- */
void show_raw ()
{
        static int amp[6] = {1, 2, 4, 8, 16, 32};
        static int page = 0;
        int pages, chn;
        char ch;

        POINTS = WLIST[W] * 512;
        pages = (long) (16384L + POINTS - 1L) / POINTS;

        cls();
        printf ("\n\n\n");
        printf ("Plot of raw data. The key list is:     \n\n");
        printf ("    w, n    wider, narrower window.    \n");
        printf ("    l, r    page left, page right.    \n");
        printf ("    +, -    increase, decrease signal  \n");
        printf ("    p       play back through DACs     \n");
        printf ("    o       send other data to plotter \n");
        printf ("    s       send speech data to plotter \n");
        printf ("    Esc     quit.  \n\n");

     printf ("Hit Enter to start.\n\n");
        kb_flush();
        do { } while (getch() != '\r');

        graf_mode();
        graf_cls();
```

```
make_grid();
memcpy (GRID, PAGE0, 32768);
plot_raw (page, amp[ADIV]);

while ( (ch = getch()) != 27 ) {
    switch (ch) {
        case 'n':
        case 'N':
            if (W < 1) { putch(7); break; }
            W--;
            POINTS = WLIST[W] * 512;
    pages = (long) (16384L+POINTS-1L) / POINTS;
            page = min (page, pages-1);
            plot_raw (page, amp[ADIV]);
            break;
        case 'w':
        case 'W':
            if (W > 4) { putch(7); break; }
            W++;
            POINTS = WLIST[W] * 512;
    pages = (long) (16384L+POINTS-1L) / POINTS;
            page = min (page, pages-1);
            plot_raw (page, amp[ADIV]);
            break;
        case 'r':
        case 'R':
            if (page > pages-2) { putch(7); break; }
            page++;
            plot_raw (page, amp[ADIV]);
            break;
        case 'l':
        case 'L':
            if (page < 1) { putch(7); break; }
            page--;
            plot_raw (page, amp[ADIV]);
            break;
```

```
            case '+':
            case '=':
                if (ADIV < 1) { putch(7); break; }
                ADIV--;
                plot_raw (page, amp[ADIV]);
                break;
            case '-':
            case '_':
                if (ADIV > 4) { putch(7); break; }
                ADIV++;
                plot_raw (page, amp[ADIV]);
                break;
            case 'a':
            case 'A':
                playback (page);
                break;
            case 'o':
            case 'O':
                chn = 1;
                send_data (page, chn);
                break;
            case 's':
            case 'S':
                chn = 2;
                send_data (page, chn);
                break;
            default:
                putch (7);
        } /* end switch */
    } /* end while */

    kb_flush();
    text_mode();
}

/* -- smoothing ---------- */
```

```
void smooth (Array, start)
 int Array[SCANS/LENV][2];
 int start;
{
      int j, k;
      int smth[SCANS/LENV];
      float mn_str, sum_str, old_pt, new_pt;

/* div by 8 before square to keep POW less than 32768. = divide by 64.
100/800 for cv 1/8sqr. Scale adjustment below. div by AD_pt to keep
amp values within roughly same range as on raw plot. low amp values
flatter, high amp values more peaked than on raw due to power function.
*/

      for (k = 0; k < 2; k++) {
           sum_str = 0;
                   for (j = 0; j < 3; j++) {
                   mn_str = (Array[j+start][k]);
                   sum_str = sum_str + mn_str;
          }
         mn_str = (float) sum_str / 3;
         smth[0] = (int) mn_str;
         smth[1] = (int) mn_str;

         for (j = 0; j < (POINTS - 3); j++) {
            old_pt = Array[j+start][k];
           new_pt = Array[j+start+3][k];
           if (Array[j+start+3][k] - 100 > Array[j+start+2][k]) {
                   mn_str = ((mn_str * 3) + Array[j+start+4][k]
                        - old_pt) / 3;
            }
            else if (j+start > 0 && old_pt - 100 >
Array[j-1+start][k])
                    mn_str = ((mn_str * 3) + new_pt -
                         Array[j+start+1][k]) / 3;
           else {
```

```
                    mn_str = max (((mn_str * 3) + new_pt - old_pt)/3,
0);
              }
              smth[j+2] = (int) mn_str;
          }
          smth[j+2] = smth[j+1];
          smth[j+3] = smth[j+1];

          for (j = 0; j < POINTS; j++) {
               POW[j][k] = smth[j];
          }
   }
}

/* -peak picking -- (removed 10-1-90) -----*/
/* void pick_peak (k, cv2_pt)
 int k, cv2_pt;
{
*/
/* this decides threshold. Peak is taken as centered above threshold. This
prevents bias by consonant release energy and should correlate with 1.
vowel peak energy and  2. p-center. Location of peak stored in A[][].
Last 5 values for speech data, first 5 for other data.   */

/* int oldflag, flag, x, y, j, c;
 char string[15];

          if (k EQ 0) c = 0;
          else c = 5;
          oldflag = 0;
          THRESH = THRESH/3;

          for (j = 0; j < POINTS; j++) {
             if (POW[j][k] > THRESH && THRESH > 0) flag = 1;
                else {
                    flag = 0;
```

```
                }
           if (oldflag != flag) {
                A[c][oldflag] = j;
                if (oldflag == 1) {
                     A[c][oldflag] = j - 1;
                     c++;
                     }
                      oldflag = flag;
                }
           } */ /* end for */
/*       if (flag == 1) {
           A[c][1] = POINTS - 1;
           c++;
           }
      if (k == 0) {
           THR1 = THRESH;
           for (j = c; j < 5; j++) {
                A[j][0] = 0;
                A[j][1] = 0;
                }
           }
      else {
           for (j = c; j < 10; j++) {
                A[j][0] = 0;
                A[j][1] = 0;
                }
           }
*/
/* -- plot threshold ----*/
/* THR1 for channel 1, THRESH for channel 2 */

/*  if (k EQ 0) y = 340;
   else y = 170;
hor_line (0, y - (THRESH / cv2_pt), 500, y - (THRESH / cv2_pt), 1);
*/
/* ----plot peak locations-*/
```

```
/* First  and last peak not plotted if beyond threshold at data start or end.
Peaks whose base is 60 msec wide or less (4 pts) not plotted as these
represent energy peaks on something other than vowels, eg. stop
consonants. */

/*   if (k EQ 0) c = 0;
       else c = 5;
    for (j = 0; j < 5; j++) {
        if (A[c][0] > 0 && A[c][1] != POINTS -1
                && A[c][1] - A[c][0] > 4)
                {
            x = XSCALE * (A[c][0] + (((A[c][1] - A[c][0])
                  + 1) / 2));
     line (x, y - 140, x, y - (THRESH / cv2_pt), 1);
                  A[c][2] = x / XSCALE;
                  }
                  else {
                        A[c][2] = 0;
                  }
            c++;
            }
      }
*/
/* --- generate envelope from data - */
void envelope (le)
      int le;
{
      int j, k, m, x;
      int huge *pr;
      long int tot0, tot1;

      pr = BUFFER;
      m = 16384 / le;
 /* points of raw per point of envelope */
      if (m < 1) return;
      for (j = 0; j < le; j++) {
```

```
            tot0 = 0L;
            tot1 = 0L;
            for (k = 0; k < m; k++) {
                  x = *pr++;
                  tot0 += abs (x);
                  x = *pr++;
                  tot1 += abs (x);
                  /* beware macros with side-effects */
            }
            AMPL[j][0] = tot0 / m;
            AMPL[j][1] = tot1 / m;
/* AMPL = measure of mean amplitude over k points of raw
data. Thus, the peaks in the plot of its (power) envelope
will not necessarily correspond to the square of the peaks
in the raw data. Ex: peak of 80 cv in raw may correspond to peak of 320
cv2, not 6400 cv2 in POWer plot.*/
      }
}

/* ---- send envelope data to plotter ------- */
void send_env (total, page, chn)
      int total, page, chn;
/* points in array (usually 128), which page to plot (0), vertical index,
horizontal window size (10), chn 2 = speech 1 = other */
{
/* amppts = range of vertical values on plot */
/* hrzpts = range of horizontal values on plot */

      int rf, j, k, c, hrzpts, pages;
      float ms_pt, msec;
      double cv2, x, y;
      char xlabel[10], ylabel[10], string[60];

      FILE * unit;
      unit = fopen ("COM2", "wb");
      TekInit (unit, 'D');
```

```
        TekCharSize (0.18, 0.30);
        TekFxd (0, 0);

        if (chn EQ 1) k = 0;
        else k = 1; /* speech k = 1; other k =0 */

        hrzpts = WLIST[W] * total / 32; /* nb 1/32 = 512/16K */

      if (total<2 || hrzpts<2) {
              putch(7);
              return;
        }

        pages = (long) (total + hrzpts - 1L) / hrzpts;
        page = min (page, pages-1);

        if (POINTS<2) {
              putch(7);
              return;
              }

        ms_pt = (float) TDIV/50 * LENV;
/* plotting factor for x axis */
         msec = POINTS * ms_pt;

/* real time msec per pt: div. sampling freq by 50 cycles/MSEC (=50
Khz) * total horizontal points = total msec in sample  */

/* ADIV = set {2,4,8,12,16,32} decreases range plotted
corresponds to screen POWer plot ranges */

        if (ADIV == 5) rf = 32;                /* 5120 */
        if (ADIV == 4) rf = 16;                /* 2560 */
        if (ADIV == 3) rf = 12;                /* 1280 */
        if (ADIV == 2) rf = 8;                 /* 640  */
        if (ADIV == 1) rf = 4;                 /* 320  */
```

```
      if (ADIV == 0) rf = 2;                    /* 160  */

      cv2 = 160 * rf;
/*range=40 screen pts/div* 4 divs* redux factor mv2 produces too large
numbers. Use cv2. POW includes a division by cv/A-D units BEFORE
the square. For the plotter, labels can't be manipulated independently of
the data plotted. To get labels right, multiply the (screen) data by the
redux factor.
[POW]: [ (AD units * 1 cv/8 AD units)**2] = cv2
*/

/*    fprintf (stdprn, "msec = %10.2f\n", msec);
      fprintf (stdprn, "ms_pt = %10.2f\n", ms_pt);
*/
    if (k == 0) TekWindow (8.50, 14.50, 0.40, 4.40);
      if (k == 1) TekWindow (8.50, 14.50, 5.60, 9.60);
/* Speech at top of paper */

      TekScale (0.00, (double)msec, 0.00, cv2);
      TekGrid ((double) msec/4.00, (double) cv2/4.00, 0.00, 0.00, 4, 4);
      for (j = (int) cv2/4; j<(int) cv2; j += (int) cv2/4) {
            TekMove (0.00, (double)j);
            TekDraw ((double)msec, (double)j);
            }
      for (j = (int) msec/4; j< (int)msec; j += (int) msec/4) {
            TekMove ((double)j, 0.00);
            TekDraw ((double)j, cv2);
            }

      TekLAxes (-(double)msec/4.00, (double) cv2/4.00, 0.00, 0.00);
      TekMove (0.00, 0.00);

/* loop which sends data from chnl 2. speech or chnl 1. to plotter ---- */

      for (j = 0; j<POINTS; j++) {
            x = j * ms_pt;
```

```
            y =  POW[j][k];
            TekDraw ((double)x, (double)y);
            }

/*          if (k EQ 1) j = THRESH;
      else j = THR1;

      TekMove (0.00, (double)j);
      TekDraw ((double)msec, (double)j);
      sprintf (string, " %d", j);
      TekMove (0.00, (double)j);
      TekLbOrg (3);
      TekLabel (string);
*/
/* plot peak locations--*/
/* First  and last peak not plotted if beyond threshold at data start or end.
Peaks whose base is 60 msec wide or less (4 pts) not plotted as these can
represent stop consonant energy peaks. */

/*       if (k EQ 0) c = 0;
      else c = 5;
       for (k = 0; k < 5; k++) {
        if (A[c][0] > 0 && A[c][1] != (int)(SCANS/LENV) -1
                && A[c][1] - A[c][0] > 4)
                   {
             x = ms_pt * (A[c][0] + (((A[c][1] - A[c][0])
                       + 1) / 2));
                   TekMove ((double)x, (double)j);
             TekDraw ((double)x, (double)(cv2 - (cv2 / 8)));
                   sprintf (string,  "%d", (int)x);
             TekMove ((double)x, (double)(cv2 - (cv2 / 12)));
                   TekLbOrg (6);
                   TekLabel (string);
              }
             c++;
             }
```

```
*/
      /* LbOrg Matrix 7 4 1
         origin: 5.  8 5 2
                 9 6 3  */

sprintf (string, "Ch %d Env %s file %s page %2d of %2d",
          chn, DATE, FILENAME, page + 1, pages);
      TekMove (5.00, (double)cv2);
      TekLbOrg (1);
      TekLabel (string);
      sprintf (xlabel, "\x0a\x0a msec");
    /* \x0a = move plot down */
    TekMove ((double)msec/8.00, 0.00);
    TekLbOrg (4);
    TekLabel (xlabel);
    /* \x0b = move plot up   */
      sprintf (ylabel, "cv");
    /* \x08 = move plot left */
      TekMove ((double)-msec/20.00, (double) 0.63 * cv2);
    TekLbOrg (5);
    TekLabel (ylabel);
      fflush (unit);
      sprintf (ylabel, " 2");
      TekMove ((double)-msec/20.00, (double) 0.63 * cv2);
      TekLbOrg (1);
      TekLabel (ylabel);
    sprintf (string, "\x07");
    /* beep to signal plot end */
    TekLabel (string);
      fflush (unit);
}

/* -- plot the envelope; second-level function ---------- */
void plot_env (total, page, cv2_pt)
      int total, page, cv2_pt;
      /* points in array, which page to plot,
```

```
        * (RAW) counts per pixel,
        * points per horizontal pixel */
{
        int lastx, lasty0, lasty1, pps;
        int pages, pix_div, width, to, x, y, j, k, c;
        float ms_div, cv2_div;
        char string[40];

        pps = WLIST[W] * total / 32;          /* nb 1/32 = 512/16K */

     if (total<2 || pps<2) {
              putch(7);
              return;
        }

        pages = (long) (total + pps - 1L) / pps;
        page = min (page, pages-1);

        FROM = page * pps;
        to   = min (FROM+pps-1, total-1);
        POINTS = to - FROM + 1;
        pix_div = 512/(10 * pages);
        ms_div = ((float) TDIV * 2000/(5 * 512)) * (float)
              pix_div;
/* convert points to ms/div = time/pt * (pt/div)/pages */
/* TDIV * 20000(ttl pts)/ 50 cycles/MSEC * 512 pts ---*/

        if (POINTS<2) {
              putch(7);
              return;
        }

        cv2_pt = max (cv2_pt, 1);
     cv2_div = (float)cv2_pt * 40;

/* convert to APPROXIMATE cv/div = cv2_pt * 40 screen pts/div. no
```

```
AD_units/cv factor required here; it's in POW square. Calibration with
oscilloscope: 0.2 Volts = 160 counts = 1V/800 counts vertical. V/div =
cpp * 40/800. Volts are too large a unit (require floats), mv too small, so
work in centivolts. 1cv/8 counts.  */

/* smooth AMPL. number of points to be smoothed = points. starting
point to smooth =FROM. */

        smooth(AMPL, FROM);
        smooth(POW, 0);

        XSCALE = 512.00/ pps;
          memcpy (PAGE0, GRID, 32768);

/* below: 1/8 = 1cv / 8 AD_units */
/* k = 0 for chnnl 1; k = 1 for channel 2 */

        for (k = 0; k < 2; k++) {
                lastx = 0;
lasty0 = (int)((float) sqr((float)POW[0][k]/8) / cv2_pt);

/*              THRESH = 0;    */

                if (k EQ 0) c = 340;
                else c = 170;

/* ch 2 plots in upper half of screen */

                for (j = 0; j < POINTS; j++) {
      y = (int)((float) sqr((float)POW[j][k]/8) /cv2_pt);
                        x = j  * XSCALE;
                        line (lastx, c - lasty0, x, c - y, 1);

/*                      THRESH = max (y, THRESH);       */

                  POW[j][k] = y * cv2_pt;
```

```
                lasty0 = y;
                lastx = x;
            }
/*        THRESH = THRESH * cv2_pt;
            pick_peak (k, cv2_pt);   */
        }

    Ggoto_xy (9, 72);
    sprintf (string, "%4d", FROM);
    gtext (string);

    Ggoto_xy (11, 72);
    sprintf (string, "%4d", POINTS);
    gtext (string);

    Ggoto_xy (17, 70);
    sprintf (string, "%3d", page + 1);
    gtext (string);

    Ggoto_xy (17, 77);
    sprintf (string, "%3d", pages);
    gtext (string);

    Ggoto_xy (19, 72);
    sprintf (string, "%9.2f", cv2_div);
    gtext (string);

      Ggoto_xy (21, 72);
      sprintf (string, "%7.2f", ms_div );
      gtext (string);

/*corresponds to INT point size (40 ms per pt) in declin.c*/

      Ggoto_xy (23, 75);
      sprintf (string, "%7.2f", ms_div/40 );
      gtext (string);
```

```
}

/* -- show the envelope; calls above routine ----- */
/* le used to be passed */
void show_env ()
{
      static int amp[6]= {2, 4, 8, 12, 16, 32};
         /* old {1, 1, 2, 4, 8, 16} */
      static int page = 0;
      int total, pages, chn;
      char ch;

      total = 16384 / LENV;
      pages = (long) (total + WLIST[W] - 1L) / WLIST[W];
      cls();
      printf ("\n\n\n");
printf ("Plot of envelope data. The key list is:     \n\n");
      printf ("    w, n     wider, narrower window.    \n");
      printf ("    l, r    page left, page right.     \n");
      printf ("    +, -     increase, decrease signal \n");
printf ("    s        send speech envelope to plotter  \n");
printf ("    o        send other envelope to plotter  \n");
      printf ("    Esc      quit.  \n\n");
      printf ("Hit Enter to start.\n\n");
      kb_flush();
      do { } while (getch() != '\r');

      graf_mode();
      graf_cls();
      make_grid();
      memcpy (GRID, PAGE0, 32768);
      plot_env (total, page, amp[ADIV]);

      while ( (ch = getch()) != 27 ) {
            switch (ch) {
                  case 'n':
```

```
case 'N':
        if (W < 1) { putch(7); break; }
        W--;
        pages = (long) (total + WLIST[W] - 1L)
                        / WLIST[W];
        page = min (page, pages-1);
        plot_env (total, page, amp[ADIV]);
        break;
case 'w':
case 'W':
        if (W > 4) { putch(7); break; }
        W++;
        pages = (long) (total + WLIST[W] - 1L)
                        / WLIST[W];
        page = min (page, pages-1);
        plot_env (total, page, amp[ADIV]);
        break;
case 'r':
case 'R':
        if (page > pages-2) { putch(7); break; }
        page++;
        plot_env (total, page, amp[ADIV]);
        break;
case 'l':
case 'L':
        if (page < 1) { putch(7); break; }
        page--;
        plot_env (total, page, amp[ADIV]);
        break;
case '+':
case '=':
        if (ADIV < 1) { putch(7); break; }
        ADIV--;
        plot_env (total, page, amp[ADIV]);
        break;
case '-':
```

```
                case '_':
                        if (ADIV > 4) { putch(7); break; }
                        ADIV++;
                        plot_env (total, page, amp[ADIV]);
                        break;
                case 's':
                case 'S':
                        chn = 2;
                        send_env (total, page, chn);
                        break;
                case 'o':
                case 'O':
                        chn = 1;
                        send_env (total, page, chn);
                        break;
                default:
                        putch (7);
        } /* end switch */
    } /* end while */

    kb_flush();
    text_mode();
}

/* --- send raw data to printer ------ */
void print_data ()

{
int j, n;
int huge *pr;
char ch, input[4];

    pr = BUFFER;
/*  printf ("*pr before 'if' block = 0x%p\n", pr);
printf ("pointer value should be ?000: if not, ERROR\n\n");
*/
```

```
printf ("*** Raw Data for Each AMPL Value ***\n\n\n");
      printf ("AMPL index ?(0 to 127)\n");
      gets(input);
      n = atoi(input) * 2 * LENV;
      pr = pr + n - 1;
printf ("INDEX   POINTER               SPEECH   OTHER\n");
      for (j = n; j < n + LENV; j += 2) {
            printf ("j  %3d   pr %p   %6d   %6d\n",
              j, pr, *pr++, *pr++);
            }
}
/* -- send contour to printer ------ */
void print_POW ()
{
int j, n;
char ch, input[4];

      printf ("ENTER to start\n");
      kb_flush();
      do { } while (getch() != '\r');
printf ("       Other       Speech              ");
printf (" Other       Speech\n");
      printf ("Index.  A[0]  P[0]  A[1]  P[1] ");
      printf ("Index.  A[0]  P[0]  A[1]  P[1]\n");
      n = (int) 16384/(LENV * 2);
      for (j = 0; j < n ; j++) {
      printf ("%4d. %4d  %4d  %4d  %4d  ", j,
                  AMPL[j][0], POW[j][0],AMPL[j][1], POW[j][1]);
      printf ("%4d. %4d  %4d  %4d  %4d\n", j+64,
                  AMPL[j+64][0], POW[j+64][0], AMPL[j+64][1],
                  POW[j+64][1]);
      }

/*    printf ("\n\n\nThreshold speech: %3d\n", THRESH);   */
      printf ("\nSpeech peaks\n");
      printf ("Index  Start  End  Diff (ms)  Plot \n");
```

```
            for (j = 5; j < 10; j++) {
             if (A[j][1] - A[j][0] != 0 ) {
                  printf ("%4d. %4d  %4d   %6.2f    %4d\n", j,
                       A[j][0], A[j][1], (float)(1 + A[j][1] -
                       A[j][0]) *(TDIV * LENV/50), A[j][2]);
                  }
            }
/* The extra 1 in printf, parameter 4, is due to inclusion of both ends of
the contour above threshold. sampling period (raw 0.14) * # points(raw
16384) = time (2.3 secs) / #points POWer (128) = ms / pt of POWer
data  */

/*printf ("\n\n\nThreshold: Other data %3d\n\n", THR1); */
    printf ("Other peaks\n");
      printf ("Index  Start  End  Diff (ms)  Plot \n");
            for (j = 0; j < 5; j++) {
             if (A[j][1] - A[j][0] != 0 ) {
                  printf ("%4d. %4d  %4d   %6.2f    %4d\n", j,
                       A[j][0], A[j][1], (float)(1 + A[j][1] -
                       A[j][0]) *(TDIV*LENV/50), A[j][2]);
                  }
            }
      printf ("From: %4d for %4d points.\n", FROM, POINTS);
      printf ("\nXSCALE factor on plot: %5.2lf\n\n", XSCALE);
      }

/* -- help message for the control loop in main() ------ */
void help()
{
      printf ("\nYou can use these keys:\n\n");
      printf ("  T   alter TDIV parameter\n");
      printf ("  R   record sound       \n");
      printf ("  A   audio speech. Press V first \n");
      printf ("  V   view raw sound\n");
      printf ("  C   calculate envelope \n");
      printf ("  E   view envelope      \n");
```

```
      printf ("  S   plot speech data. Type V first   \n");
      printf ("  O   plot other data. Type V first   \n");
printf ("  S  plot speech envelope. Type E first. \n");
      printf ("  O   plot other envelope. Type E first \n");
      printf ("  P   print raw values \n");
      printf ("  I   print POWER values \n");
      printf ("  W   write POWER data to disk \n");
    printf ("  F   write raw data to disk\n");
      printf ("  D   get data from file   \n");
      printf ("  Q   quit program         \n");
      printf ("  H   help; this message   \n\n");
}
/*------------- main --------------- */
main ()
{
      static int gain[8] = { 0,0,0,0, 0,0,0,0 };
      static int channels[8] = {0,1,2,3,4,5,6,7};

      int result, j, k;
      unsigned long a, b;
      char ch, input[80];
      int huge *p1;
      int huge *BUF_BACKUP;

      /* --- LabMaster board initialisation functions --- */
      check_vector (0x66);              /* Is Labpac there */
      result = labpac (RESET);
      result = labpac (TIINIT, TIMER);
      result = labpac (AIINIT, ATOD, 8, 1, gain);
                  /* eight input channels; DMA channel 1 */
      result = labpac (AOINIT, DTOA, 2);

      /* ---------- Introduction ---------- */
      cls();
      freopen ("PRN","w",stderr);
      printf ("\n\n\nSound program.\n\n");
```

```
      printf ("DATE ( dd-mm-yy) ? \n\n");
      gets(DATE);
      printf ("Press ENTER to begin.\n\n");
      kb_flush();  do { } while ( getch() != 13);

      /* ----------------------
* Halloc() memory; 128 KB is guaranteed to span a full 64 KB
* region starting on some 0x?000:0000 boundary.
* -------------------------------  */

p1 = (int huge *) halloc ( 32L *1024L, 2 * sizeof(int));
      if (p1  == NULL) {
            printf ("Can not halloc().\n");
            labpac (RESET);
            exit (1);
      }

      a   = ptol (p1);   /* bytes from start of memory */
      b   = (long) (a + 0x0000ffff) & 0xffff0000;
      BUFFER = ltop (b);
    BUF_BACKUP = BUFFER;

      printf ("start of buffer is   %p.\n", p1);
      printf ("recording starts at  %p.\n", BUFFER);

      /* ---------- main loop ---------- */

      for (;;) {           /* forever */
             BUFFER = BUF_BACKUP;
            printf ("----Main loop----\n");
printf ("Choices: T R A D F W P I V C E S O Q;");
            printf (" H for help.\n");
            kb_flush();
            switch (getch()) {
                  case 't':
                  case 'T':
```

```
printf ("  TDIV = %d. Change to ", TDIV);
                  j = atoi(gets(input));
                  if (j != 0) {
                        j = max (j, 3),
                        j = min (j, 100);
                        TDIV = j;
                  }
                  printf ("  Set to %d.\n", TDIV);
                  break;
            case 'r':
            case 'R':
printf ("Record; hit Enter to begin.\n");
                  kb_flush();
                  do { } while (getch() != '\r');
                  record (BUFFER);
                  break;
            case 'd':
            case 'D':
printf ("Get data from file; press Enter.\n");
                  kb_flush();
                  do { } while (getch() != '\r');
                  printf("FILENAME (14 chars max) ? \n");
                  gets(FILENAME);
                  read_data();
                  break;
            case 'a':
            case 'A':
printf ("Audio. Press V for access\n");
                  break;
            case 'v':
            case 'V':
                  show_raw ();
                  break;
            case 'c':
            case 'C':
                  printf ("Envelope calculation.\n");
```

```
                    printf ("How big an envelope?\n");
     printf (" (Choose one of 1024, 512, 256, ");
                    printf ("128, 64, 32.)\n");
                    printf (" (Old size was %d.)\n", LENV);
                    do {
                         j = atoi (gets(input));
                    } while (j!=1024 && j!=512 && j!=256 &&
                         j!=128 && j!=64 && j!=32 && j!=0);

/*                  if (j!=0) LENV = j; */
                    printf ("Envelope size = %d.\n", LENV);
                    envelope (LENV);
                    break;
               case 'e':
               case 'E':
                    show_env (LENV);
                    break;
               case 'S':
               case 's':
               case 'o':
               case 'O':
                    show_raw ();
                    break;
               case 'f':
               case 'F':
                    printf ("Save raw data.\n");
                    save_raw ();
                    break;
          case 'w':
               case 'W':
                    printf ("Save POWER data.\n");
                    save_POW();
                    break;
          case 'i':
               case 'I':
    printf ("Print POWER data AFTER E.\n");
```

```
                                print_POW();
                                break;
                        case 'p':
                        case 'P':
                                printf ("Print raw data.\n");
                                print_data ();
                                break;

                        case 'q':
                        case 'Q':
                                goto bottom;
                                break;
                        case '?':
                        case '/':
                        case 27:
                        case 'h':
                                help();
                                break;
                        default:
        printf ("Try typing 'h' for help.%c\n", 7);
                } /* end switch */
        } /* end for */

bottom:
        printf ("Experiment over.\n\n");
        labpac (RESET);
        hfree ((char far *)p1);
        exit (0);
}
```

APPENDIX 3

THE ENTRAINMENT INDEX

A3.1 The Entrainment Index

The entrainment index was devised to fill the need for a measure of the proximity of the subject's period to perfect multiples or submultiples of the stimulus period. Pictorially, the problem is represented in Figure **A3.1**. Figure **A3.1A** shows the subject's period approximating the stimulus period, and in Figure **A3.1B** the mean periods are quite different. (The mean period is calculated as the mean interval between successive peaks. The actual stimulus data have not been plotted in the figures in this appendix, as only the resulting stimulus peaks are necessary to illustrate the concepts discussed here.)

The aim was to devise a measure that would represent the difference between the subject's period and the stimulus period in a uniform way, regardless of the order of the subject's period with respect to the stimulus period. (Order here represents the degree of complexity of the ratio of the subject to the stimulus period. A 1 : 1 ratio is regarded as simple, and is referred to as first order; a ratio of 2 : 1 is referred to as second order, and so on.) So the aim is to represent by the same value on the measure a subject's period that is just over double the stimulus period

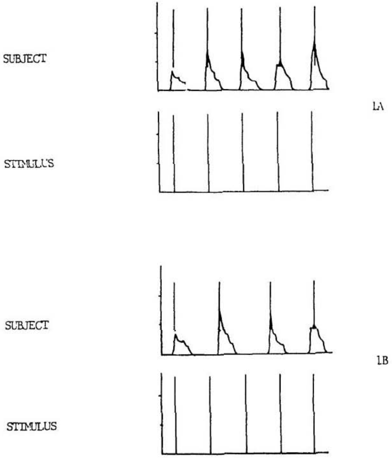

Figure A3.1. Relationships between the subject and stimulus movements. Upper graphs show subject monosyllable repetition. Lower graphs show stimulus movement. Scale: The interval between the first two stimulus peaks equals 1560 ms. The mean stimulus period in A and B is 1560 ms. Subject's mean period: A. 1612 ms; :B. 2136 ms.

(Figure **A3.2**), and a subject's period that is slightly longer than the stimulus period (Figure **A3.1A**). The following exposition considers first

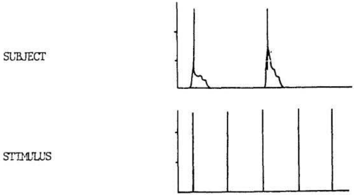

Figure A3.2. Periods that stand in close to 2 : 1 ratio. Upper graph: subjec movement. Lower graph: stimulus movement. Scale: the interval between the first two stimulus peaks equals 1560 ms. Mean stimulus period: 1560 ms; subject's mean period: 3200 ms.

the case where the subject's period is longer than or equal to that of the stimulus under the heading of the multiple scale, and secondly, the case where the subject's period is shorter than that of the stimulus (the submultiple scale).

A3.1.1 The Multiple Scale

The relative deviation of the subject's period from the stimulus period was calculated by dividing the longer period by the shorter period, and retaining the argument (the digits to the right of the decimal point) for calculations.

Relative Deviation = Longer Period/ Shorter Period (1)

The continuous scale that results is represented in Figure **A3.3** as a clock face. The values of the argument range from .00 to .99, with .00 representing the case where the subject's mean period and the mean stimulus period are identical, or entrained. In this thesis I consider values from .90 to .10 to indicate approximate entrainment of subject to stimulus period, as shown by the dashed lines on the clock face. This means that the mean subject period must be within ±10% (called the cut off value) of the stimulus period length to qualify as approaching entrainment.

These values are more stringent than those adopted in the literature for a similar study (eg. Smith et al., 1986), where entrainment-like behavior was considered to occur if one movement period was within ± a quarter of the length of the other, which corresponds to a value between +.25 and approximately .75 (about .00) on the scale here.

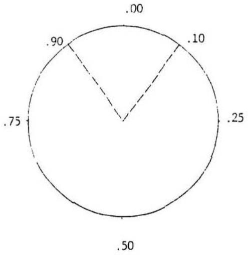

Figure A3.3. The relative deviation scale.

The closer the argument is to 0, the closer to a perfect integer ratio is the ratio of the stimulus period to the subject's period. As long as the subject's period was greater than the stimulus period, this produced an unproblematic multiple scale. Table **A3.1** presents the relative deviation for the data shown in Figures **A3.1** and **A3.2**. The relative deviation has been multiplied by 100 and rounded to the nearest integer to produce an integer scale for the argument. The scale ranges from 0 to 99, so the two underlined digits to the left of the decimal point now represent what earlier was the argument. The leftmost

Table A3.1 The multiple scale of the entrainment index

Figure	**A3.1A** Stim	**A3.1A** Sub	**A3.1B** Stim	**A3.1B** Sub	**A3.2** Stim	**A3.2** Sub
Period	1560	1612	1560	2136	1560	3200
R. Dev.	103.0		137.0		205.0	

Note: Periods are in ms; R. Dev. = relative deviation, Stim = stimulus, Sub = subject.

digit (not underlined) represents the order of the relationship of the periods. For example, if the subject's period is between twice and thrice as long as that of the stimulus, the leftmost digit will be 2, as in the third column of Table **A3.1**.

It can be seen that the underlined digits in the relative deviation values for the data shown in Figures **A3.1A** and **A3.2** are very similar. That is appropriate, given that the subject's period in Figure **A3.1A** is close to a multiple of the stimulus period, and in Figure **A3.2** is close to double the stimulus period. The measure thus can indicate proximity to entrainment, irrespective of the order of the relationship between subject and stimulus period. It is also fitting that the underlined value in the middle column of Table **A3.1** is distant from 0 and 99, for the mean subject and stimulus period are dissimilar in Figure **A3.1B**.

To avoid the problems of calculating with a clock-like scale that wraps around, as does that shown in Figure **A3**, the values of the relative deviation that were greater than 50 were converted to values between 0 and 50 as follows:

Entrainment Index = 50 - (Relative Deviation - 50) (2)

This meant that a clock scale value of 90 became 10. The intervals on this new scale remain equivalent. An example of the way this scale would be used is shown in Table **A3.2**.

If the subject's mean period were 1100 msec, and that of the stimulus 1000, the value of 10 would ultimately arise from division using formula (1) and multiplication by 100 (bottomr row, 2nd numeric column, Table **A3.2**). If, on the other hand, the subject's period is 1900, and that of the stimulus remains 1000, application of formula (1) and multiplication by 100 would yield a value of 90, which would then be converted, following formula (2), to 10 (bottom row, 4th numeric column, Table **A3.2**). Thus, the subject's period is 10% longer (case 1) or 10% shorter (case 2) than twice that of the stimulus, and so in

Table A3.2. Derivation of entrainment index values

	Stimulus	Subject	Stimulus	Subject
Period	1000	1100	1000	1900
R. Dev.	(1100 / 1000) * 100		(1900 / 1000) * 100	
	110		190	
E.I. Calc.	Order	R. Dev.	Order	R. Dev.
	1	10	1	90
	-	-	1	10
E.I.	1	10	1	10

Note: E.I.: Entrainment Index (multiple scale); Calc.: calculation; R. Dev.: relative deviation; period is in ms.

percentage terms, the relative deviation of the subject's mean period from that of the stimulus, or of one of its multiples, is the same.

A3.1.2 The Submultiple Scale

Up until now, only the cases where the subject's mean period has been longer than, or equal to, the stimulus period have been considered. This leaves the cases where the subject's period is shorter than that of the stimulus. To these cases the submultiple scale applies. Formulas (1) and, where appropriate, (2) were applied to the data, just as described above for the multiple scale.

The submultiple scale preserves the meaning of the multiple scale in two important respects: a) the closer a scale value is to 0, the closer to a perfect integer ratio stand the mean subject and stimulus period, and b) a value close to 50 indicates that the ratio of the two mean periods is distant from perfect multiplicity.

However, it must be noted that once the subject's mean period is placed in the divisor, which occurs when formula (1) is applied, the relative deviation is now that of the stimulus period as a percentage of the length of the subject's period. To illustrate this point Figures **A3.4** and **A3.5** are provided. In Figure **A3.4**, the subject period is very slightly shorter than the stimulus period, while in Figure **A3.5**, the subject's mean period is much shorter than that of the stimulus. The entrainment index values that arise from the data shown in these two figures are given in Table **A3.3**. In Table **A3.3**, the entrainment index value of 11 for the data of Figure **A3.4** correctly implies that the subject's period is similar to that of the stimulus. The stimulus period deviates from the value of the subject period by 11% of the subject period.

The entrainment index value that arises for the data in Figure **A3.5** (see Table **A3.3**) indicates that the stimulus period should deviate from the subject's mean period by 13% of the subject's mean period. This is so, if the order of the ratio is included in calculation:

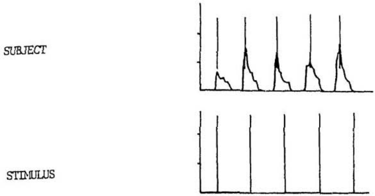

Figure A3.4. The first order (approximately 1 : 1) case. Upper graph: subject; lower graph: stimulus. Scale: the interval between the first *two stimulus peaks equals 1560 ms. Mean stimulus period: 1560 ms;* subject's mean period: 1403 ms.

$$\text{Dev.} = \frac{\text{Longer Period - (Order * Shorter Period)}}{\text{Shorter Period}} \qquad (3)$$

$$13 = \frac{1560 - (2 * 732)}{732}$$

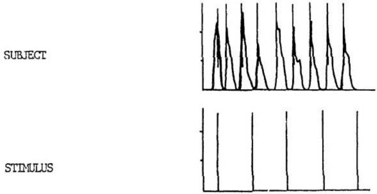

Figure A3.5. The submultiple index. Upper graph: subject. Lower graph: stimulus. Scale: the interval between the first two stimulus peaks equals 1560 ms. Mean Stimulus period: 1560 ms; subject's mean period: 732 ms.

The submultiple scale value then indicates, as did the multiple scale, the deviation of one period from the other; it is just that the reference has changed. Now the subject period is the reference.

This similarity in the meanings of the values of the two scales has been stressed because it is not common in experimental research to cast one's measures in terms of the dependent variable, here the mean subject period. Generally, one wishes to look for changes that are due to an

Table A3.3. Derivation of submultiple scale values

	Stimulus	Subject	Stimulus	Subject
Period	1560	1403	1560	732
R. Dev.	(1560 / 1403) * 100		(1560 / 732) * 100	
	111		213	
E.I. Calc.	Order	R. Dev.	Order	R. Dev.
	1	11	2	13
	-	-	-	-
E.I.	1	11	2	13

Note: E.I.: Entrainment Index (multiple scale); Calc.: calculation; R. Dev.: relative deviation; period is in msec.

independent variable, such as the stimulus period, and so deviations would sensibly be referred to as deviations from some value of the stimulus variable.

The assumptions about entrainment that I have made are best served by allowing the stimulus period in the numerator where necessary. First, if one assumes that the subject can entrain at submultiples of the stimulus period, for example, half of the stimulus period, then it is preferable to associate a single value, here 0, with perfect multiple or submultiple relationships. This cannot be done if either the stimulus period or the subject's period must invariably be in the denominator, irrespective of the relative length of the two periods. In addition, a similar study (Smith et al., 1986) has also consistently used period length, not period source, as the criterion for placement in the divisor for calculation of the ratio of finger movement and syllable repetition frequency.

If entrainment does not tend to occur, values close to and distant from 0 on both submultiple and multiple scales should be equally probable in the data. That would not be true for the submultiple index if the stimulus period remained in the denominator at higher order relationships.

Following the procedure that I have outlined above, the entrainment index indicates the degree of proximity of the subject to the stimulus period, regardless of the order of the relationship. For example, for the data in Figure **A3.5**, the entrainment index value of 13 correctly suggests that the subject period is close to a submultiple (half) of the stimulus period.

A low entrainment index value on either scale suggests proximity of the subject period to the stimulus period, or proximity to a submultiple of the periods. The usual entrainment index cutoff value of 10 simply refers to 10% of the smaller of the subject's and the stimulus mean periods.

A3.2 Ensuring the Validity of the Entrainment Index

It was expected that period length would not vary radically and in a patterned way within a sample, for large and patterned variation could result in misleadingly low or high entrainment index values (see Figure **9.5** in Chapter **9** and the accompanying discussion). At the same time, it was necessary to allow for changes in period that might occur as the subject switched from moving out of phase to in phase with the stimulus (see Kelso et al., 1981; Kelso et al., 1983; Scholz & Kelso, 1989 and 1990 for examples), or as the subject began to synchronize with the stimulus rhythm.

One way of checking that the pattern of variation in the period is acceptable is to monitor the lag of the subject's movement relative to that of the stimulus. (The stimulus period scarcely varied over a 15 sec sample. See section **8.2.2** for a definition of lag.) The lag should not show an alternating pattern if the resulting entrainment index value is to be considered valid (eg. Figure **9.5**).

The variance of the relative phase is based upon the lag, and is a good indicator of entrainment, for it reveals if the subject is consistently repeating a syllable or reaching the lowest position with the finger at the same phase relative to the stimulus cycle. Since the interval between stimuli changed gradually over the experiment, the variance of the relative phase is particularly important to judging whether the subject maintained a constant lag relative to the stimuli.

For these two reasons, standards for variability needed to be defined. Then, these standards could be used as filters. Samples with too high a variance of the relative phase could be removed from analyses in which a very stable period was particularly important, namely the relative phase analyses. This would honour the assumption that the mean period, upon which the index is based, represented a relatively consistent sample value. There is nothing in the literature to adopt as a standard, nor any discussion of the problem that could serve to guide the endeavour. Thus the standards were developed empirically.

There were two intentions: a) to ensure that the lag, and therefore, the period, of the subject's movement was not patterned, and b) to filter out data where the relative phase did not appear to be stable across the entire sample. The first intention (a) could be fulfilled by looking at the pattern of relative phase values for every sample to check that they did not alternate regularly and inappropriately, as in Figure **9.5**. This was done for all entrainment index values that contributed to Tables **11.3** and **11.4**.

The second intention (b) was particularly important for analyses in which the values from one sample would be examined in isolation, for example, the analysis of relative phase. In addition, the main interest in the analysis of relative phase was stable entrainment, and so a strict criterion for variability was required (see section **11.4**). This criterion is described below.

When the sample size was small, more stringent restrictions were placed upon the level of variance that could be deemed acceptable, since the sampling error is larger with smaller samples.

Lag was calculated as the interval between the peak in the subject's data and the nearest peak in the stimulus data, relative to the bracketing peak to peak interval of the stimulus data. This number was cast as a percentage, and has been called <u>relative phase</u> (see section **8.2.2**).

Table A3.4 Lag calculation

	Stimulus Peaks	Subject Peaks
Time of occurrence (ms)	1050	480
	2180	1620
	3220	2700

In Table **A3.4**, the first subject peak is not enclosed (bracketed) by stimulus peaks, and so no lag is calculated. The second subject peak is closer in time to the second stimulus peak than to the third stimulus peak, and so the resulting relative phase is:

$$-49.6\% = 100 * (1620 - 2180) / (2180 - 1050)$$

The value that arises from (1620 -2180) in the numerator is the lag, in ms. The next relative phase values are similarly calculated, using the third data value of the subject and the enclosing stimulus peaks:

-50% = 100 * (2700 -3220) / (3220 - 2180)

The negative relative phase value indicates that the subject peak is in advance of the stimulus peak; positive phase values indicate that the subject follows the stimulus.

Table A3.5. Samples with unacceptably high variance

N	2	3	4	8	12
s^2	4.5	9.3	39	139.9	178.3
Phase	47	47	49	49	48
	50	49	44	44	50
		43	38	38	44
			35	30	47
				25	46
				23	44
				22	41
				15	33
					31
					22
					19
					9

The mean relative phase value and the variance about the mean (based on N - 1 subject peaks) were calculated for each sample. Table **A3.5** presents data that were considered to show too much drift away from stable relative phase values, here approximately 50%, to be acceptable in the analysis of relative phase. The sample size is given at the heading of each column, and the data presented are relative phase values cast as percentages. The variance for each sample is given directly beneath the sample size. The phase variance cutoff values that were used to filter out unacceptably inconsistent data are given in Table A3.6.

Table A3.6 Criteria for entrainment index values in relative phase analysis

N	2	3	4	5	6	8	10	12
Max s^2	4	9	36	64	81	121	144	169

Note. N: number of calculations of relative phase within the 15 second sample; Max s^2: Maximum acceptable variance of the relative phase value within a 15 sec sample of data.

In the full set of experimental data, the median was 9 relative phase calculations per 15 second sample. Only one subject (S9) generally produced fewer than 5 peaks per sample; her repetitions were extremely slow. The relative phase variance cutoff value of 169 (for samples with 12 calculations contributing to the variance) was also applied to samples with more than 12 calculations.

To qualify for the relative phase analysis, a 15 second sample had to yield a entrainment index value less than 10 and show a relative phase variance less than, or equal to, that appropriate for the given number of calculations, as shown in Table A3.6.

A3.3 Improvements upon Previous Experimental Techniques

The analytical methods introduced here improve upon those used by Smith et al. (1986), whose paper presents the most experimental data about entrainment in human speech. In the past, collecting and analyzing samples of speech sound by computer have been limited by the great demand speech places on computer memory. Analysis of more than 5 seconds of speech at once was difficult to achieve as recently as 1985.

The samples used as basis for period calculation here are long, 15 seconds, compared to 10 seconds in Smith et al.'s work. Long samples are important for observing the stability of processes like entrainment. The longer sample length was possible because frequency analysis procedures such as spectral analysis were avoided, reducing computer memory requirements. Smith et al. (1986) state explicitly that a better method than spectral analysis could probably be devised for their data.

The procedures followed here were devised to address some of Smith et al.'s problems. My digitization and data analysis programs discard as much irrelevant information as possible, during the digitization of sound, saving memory, and enabling longer samples to be digitized.

The programs calculate only one period, rather than providing a spectrum of frequencies from which a human rater must select the main frequency (eg. Smith et al., 1986). The problems of reliability that arise using humans are thus avoided. Instead, through pilot work, the programs were refined so that they reliably picked the peak vowel energy in certain types of monosyllables.

Smith et al. cannot deal numerically with submultiple and multiple frequency ratios, which reduces the clarity of their presentation and unnecessarily limits their numerical analyses and conclusions. The entrainment index devised here solves that problem.